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BREADBOARD RL10-IIB LOW-THRUST TEST (SECOND ITERATION) FINAL REPORT

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FOREWORD

Pratt & Whitney conducted a series of engine tests demonstrating RL10-IIB rocket engine operation at reduced thrust levels during December 1987 and January 1988. The program was a second iteration of the breadboard engine testing effort conducted in February 1984 and described in Reference 1. Two new heat exchanger designs were tested to determine their performance in the engine cycle. This report summarizes the engine testing performed and is submitted in compliance with the requirements of NASA Lewis Research Center Contract NAS3-25052.

The testing was headed by Robert R. Foust, Senior Project Engineer. The principal engineers involved in testing were Paul G. Kanic and Robert W. Marable. The effort was monitored by NASA representative Richard L. DeWitt, Product Improvement Program Technical Monitor.

The individuals who have made significant contributions to the test program and the preparation of this report are D.E. Galler, R.B. Kaldor, D.J. Varella, and P.M. Watkins.

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SUMMARY

The RL10-IIB breadboard demonstrator engine XR201-2 completed a 19-run test series on 19 January 1988. The series was conducted to evaluate the performance of two oxidizer heat exchanger designs within the engine system. The first heat exchanger tested was a high heat transfer design that used a high heat flux through a compact aluminum core and attenuated oxidizer flow oscillations in an integral volume. A low heat transfer design attenuated oscillations by gradually transferring energy from hydrogen to oxygen, making use of a vented resistance layer to impede heat transfer. Engine operation was demonstrated at tank head idle and pumped idle. Stable engine operation was attained at tank head idle; however, pumped idle operation was unstable primarily due to the inability of the engine to supply propellants to the heat exchanger at the design conditions. The test results indicate that further testing concentrating on propellant flow and pressure adjustments may reduce the level of instability.

INTRODUCTION AND BACKGROUND

Space engines using cryogenic propellants require a cooling process to condition the engine to operating temperature prior to start. This process has previously been accomplished by flowing propellants through the engine and then discarding the propellants overboard, which is an inefficient conditioning method. A process that permits burning of the propellants (gases, liquids, or mixtures) during conditioning would be a significant improvement to the process. The resultant thrust production would be useful for settling propellants to the vehicle tank exit, since space vehicles are typically operating at a zero gravity condition. Auxiliary propulsion systems are currently required to perform this function. This low thrust level is called the tank head idle (THI) operating mode.

The engine is thermally ready to start following a period of conditioning at THI; however, high performance rocket engine propellant pumps require net positive suction pressure (NPSP) to prevent cavitation. This NPSP requirement is currently accomplished by low performance auxiliary boost pumps or vehicle tank pressurization systems using an independent pressurizing gas such as helium. The improved scheme permits operation at a low thrust level of approximately 10 percent (called pumped idle or PI) with liquid propellants that do not require net positive suction head because the pumps are operating at low speed. In this mode the engine can supply propellants at pressure and temperature conditions that can be used to pressurize the vehicle tanks, thus eliminating an auxiliary pressurizing system. The engine may be operated in this mode as long as required for vehicle maneuvering, deployment of payloads where low acceleration is desired to minimize payload structural impacts, or for tank pressurization prior to acceleration to full thrust.

During operation at low thrust levels, high density changes between propellant phases confronts the engine with significant changes in thrust chamber coolant flow and widely varying combustion mixture ratios. This process must be attenuated. The biggest change in mixture ratio would occur if the oxygen condition changed rapidly and liquid with pockets of gas were alternately injected into the combustion chamber. This mixture ratio change can be minimized if only gaseous oxygen were available for injection. A similar problem does not occur in the hydrogen system because the hydrogen is always gasified as it cools the thrust chamber tubes before injection into the combustion chamber. Oxygen gasification prior to injection provides a satisfactory level of control. The warm hydrogen gas available after thrust chamber cooling provides a source of energy for gasifying the oxygen in a gaseous hydrogen/oxygen heat exchanger. The heat exchanger could eliminate an active control system and improve engine performance by optimizing propellant injection velocities into the combustion chamber.

Background information concerning the engine configuration can be found in Reference 2.

The test series demonstrated engine operation using two different heat exchanger configurations to vaporize liquid oxygen. Although the majority of the engine hot time was at THI levels, some PI run time was accumulated on one heat exchanger unit.

OBJECTIVE

The objective of this test series was to determine the feasibility of using two different oxidizer heat exchanger designs in the breadboard engine system. Operation at THI and PI was to be evaluated. Of particular interest was the start transient and the transition from THI to PI. Information obtained from this test series could provide input for improved engine and heat exchanger designs prior to future low thrust testing.

ENGINE CONFIGURATION

The configuration of the RL10-IIB breadboard engine design is described in Reference 2; however, the original two-piece heat exchanger was replaced with one of the single self-contained configurations described below. The breadboard engine configuration tested is shown schematically in Figure 1.

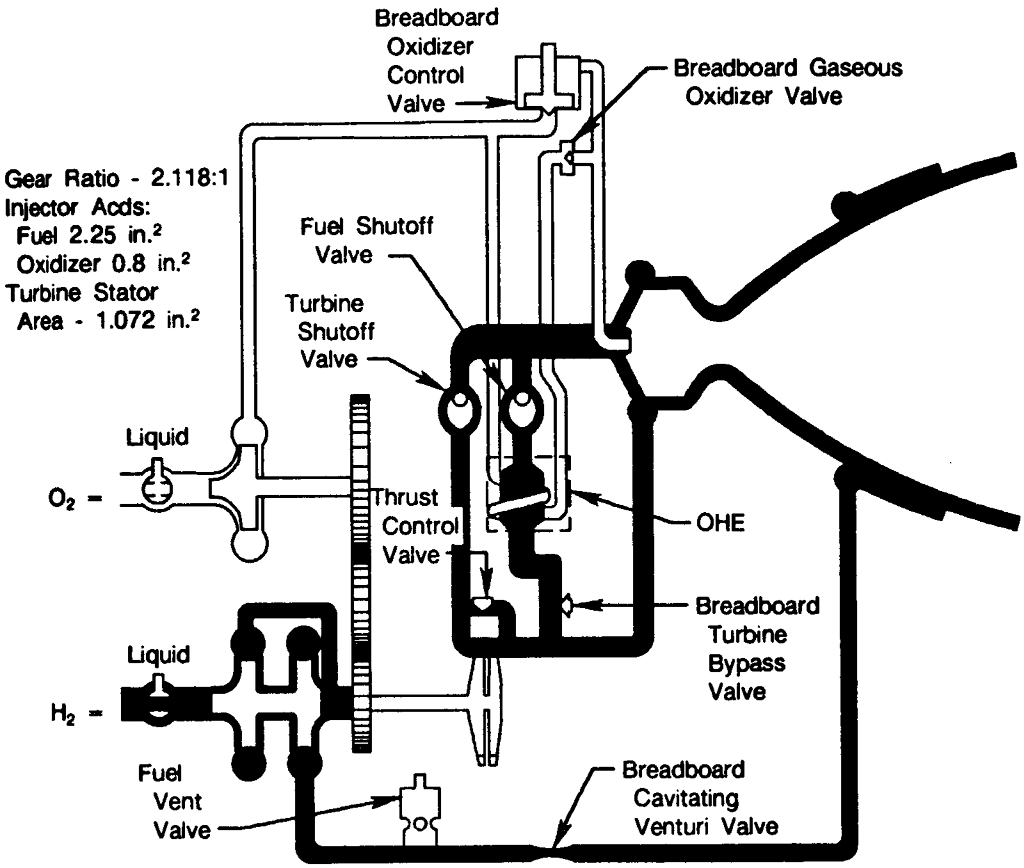

Figure 1. Breadboard RL10-IIB Engine Flow Schematic

The RL10-IIB engine tested was designated as XR201-2. It was an RL10A-3-3A model with the following major changes (as shown in Appendix A):

1. Oxidizer heat exchanger (OHE) added
2. Four hydraulically actuated valves added:

    a. Gaseous oxidizer valve (GOV)
    b. Oxidizer control valve (OCV)
    c. Cavitating venturi valve (CVV)
    d. Turbine bypass valve (TBV)

3. Pump gear ratio changed
4. Single-bearing idler gear incorporated
5. Injector with torch igniter features incorporated

6. Dual ignition systems with a torch igniter installed
7. Reduced area turbine stators installed
8. No interstage cooldown valve installed
9. Modified pump discharge cooldown valve installed (fuel vent valve or FVV).

This engine was previously operated as XR201 Build 1, on which the first-iteration heat exchanger was run in February 1984. The major engine differences from the previous build include (as shown in Appendix B):

1. Two new OHE configuration designs:

    a. High heat transfer (HHT)
    b. Low heat transfer (LHT)

2. The torch igniter hydrogen supply was replumbed to provide hydrogen from the chamber jacket discharge. This increased hydrogen flow to the igniter during steady-state engine operation, thus reducing mixture ratio and resultant heat damage to the igniter.

Engine buildup was completed on 11 November 1987, and the engine was sent to the E-6 test stand for testing on 24 November. Photos taken of the engine prior to delivery to the test stand (with the high heat transfer heat exchanger installed) are shown in Figures 2 through 6. Photos of the engine mounted in the test stand (low heat transfer heat exchanger installed) are presented in Figures 7 and 8.

A description of the engine components can be found in Appendix A. The OHE configurations are described in detail in Appendix B.

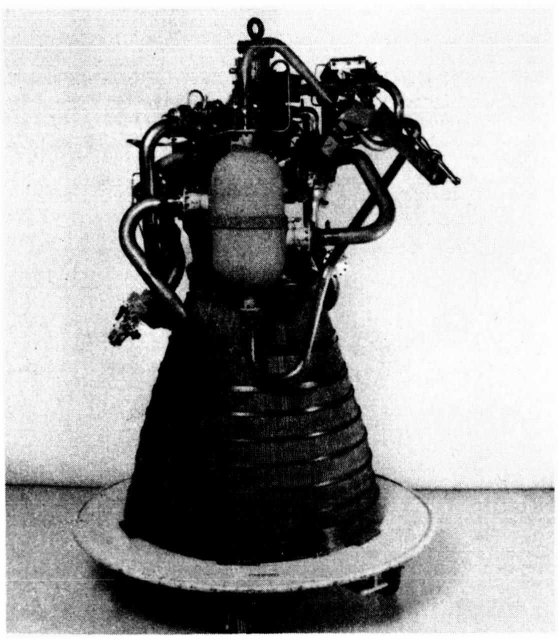

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Figure 2. RL10-IIB Engine XR201-2 (High Heat Transfer Heat Exchanger Installed), View 1

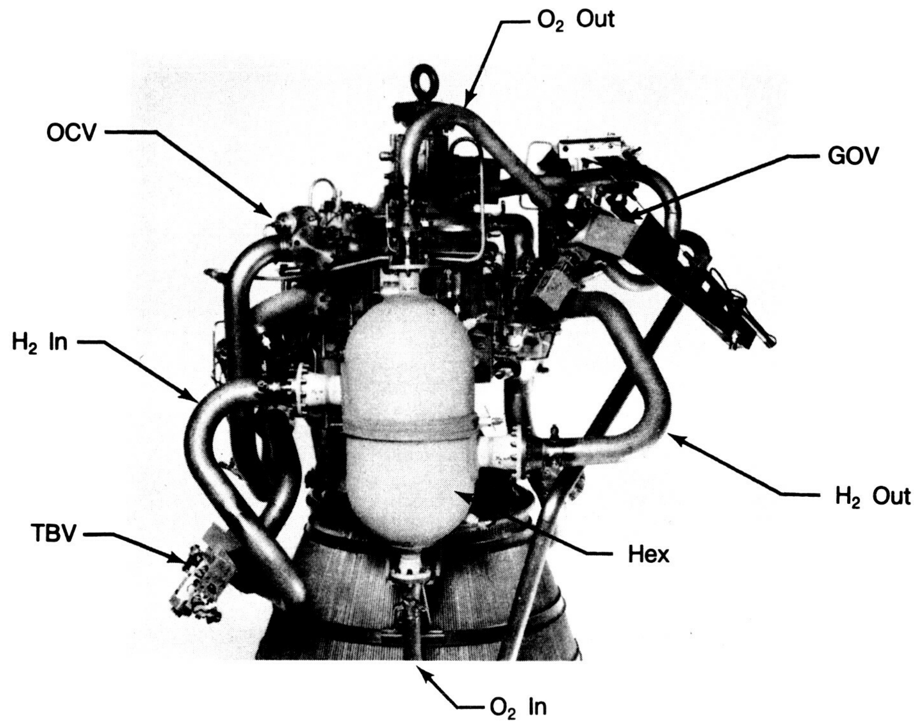

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Figure 3. RL10-IIB Engine XR201-2 (High Heat Transfer Heat Exchanger Installed), View 2

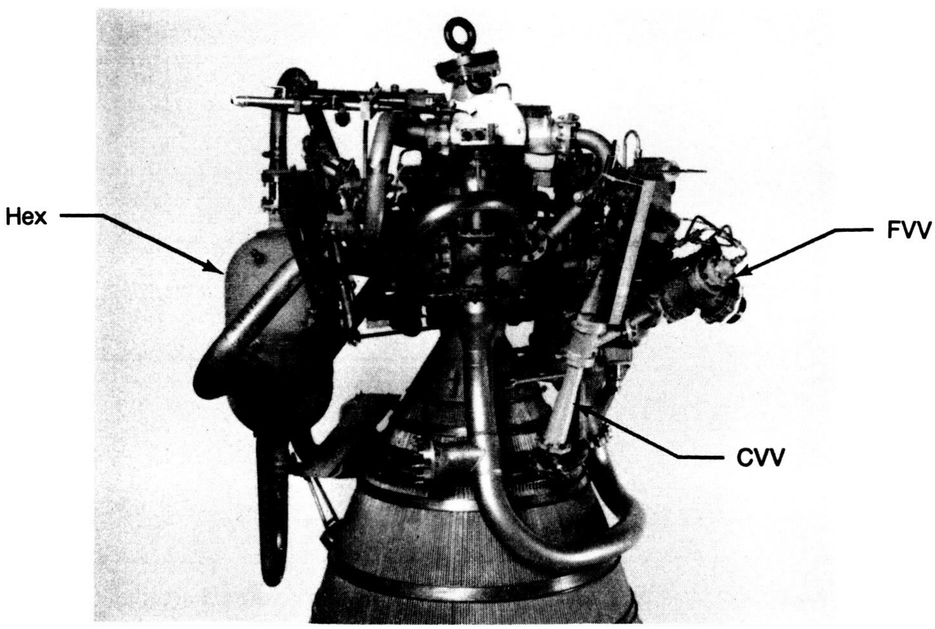

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Figure 4. RL10-IIB Engine XR201-2 (High Heat Transfer Heat Exchanger Installed), View 3

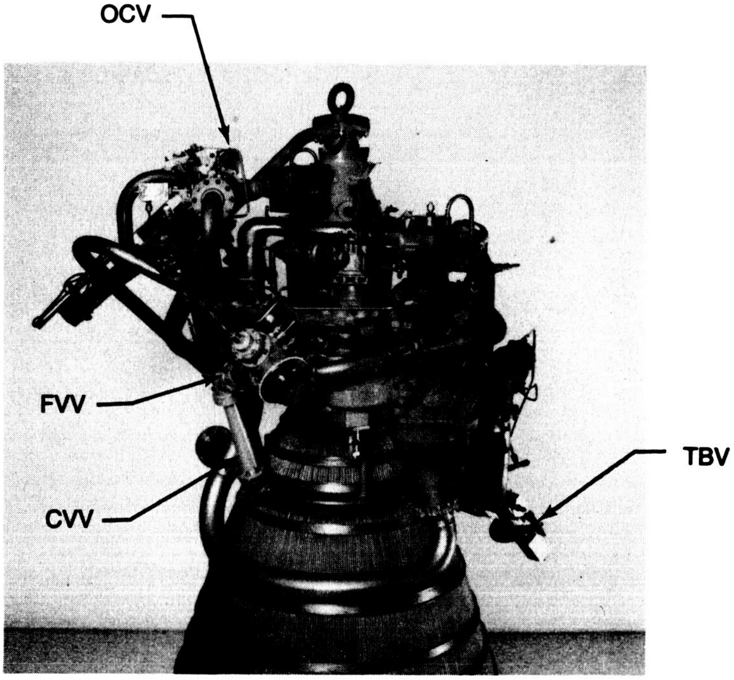

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Figure 5. RL10-IIB Engine XR201-2 (High Heat Transfer Heat Exchanger Installed), View 4

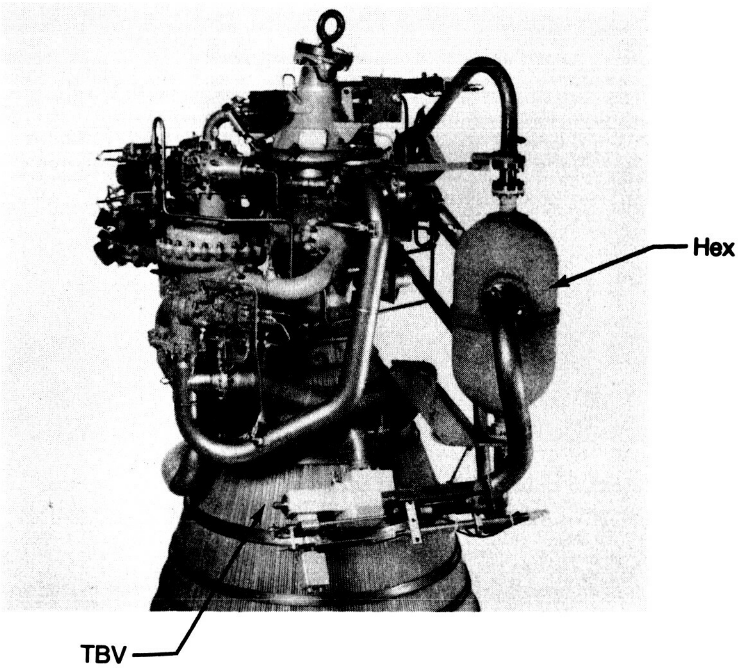

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Figure 6. RL10-IIB Engine XR201-2 (High Heat Transfer Heat Exchanger Installed), View 5

LHT OHE

Test Capsule

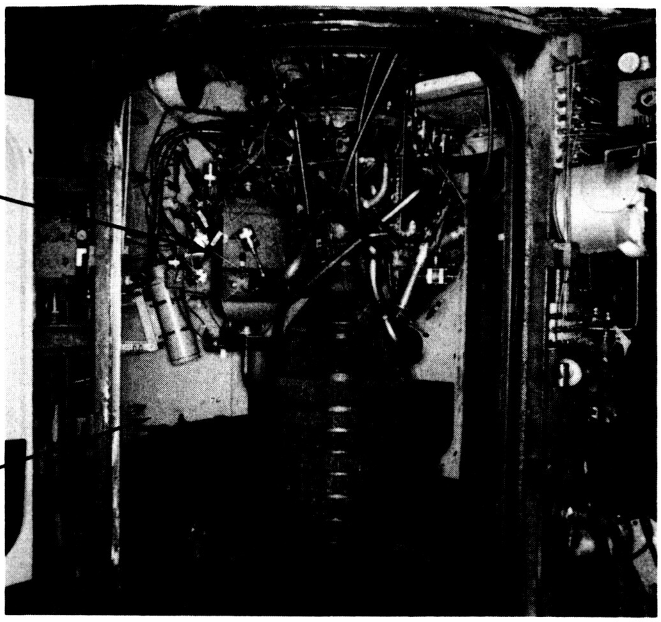

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Figure 7. RL10-IIB Engine XR201-2 Installed in Test Stand E-6 (Low Heat Transfer Heat Exchanger Installed), View 1

LHT OHE

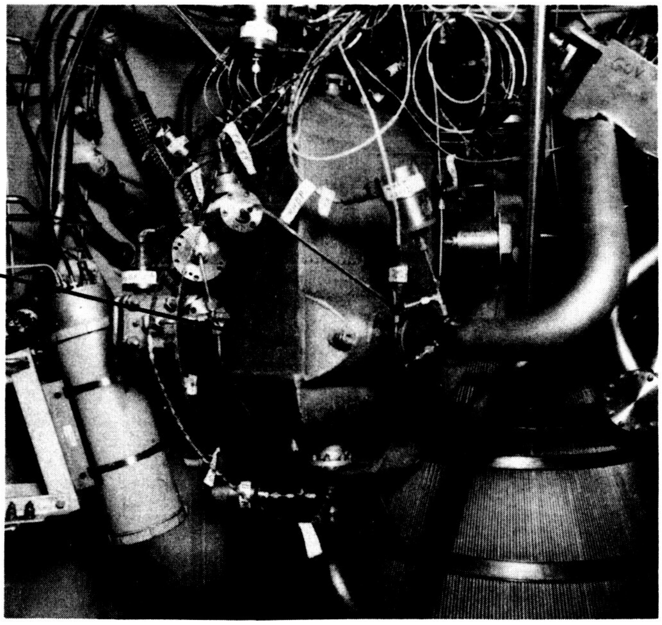

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Figure 8. RL10-IIB Engine XR201-2 Installed in Test Stand E-6 (Low Heat Transfer Heat Exchanger Installed), View 2

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TEST SUMMARY

Engine XR201-2 completed nineteen firings during this test program. A test summary is shown in Table 1. The objective of each run was to start and run at THI, then transition to PI. The following is a description of each run:

Hot Run 16.01 was aborted 0.214 second after start. The low chamber pressure (Pc) abort was triggered when chamber pressure failed to reach the specified level of 6.0 psia. The data indicated that the engine ignited; however, chamber pressure did not increase as quickly as anticipated. Prior to the next run, the abort pressure level was changed to 2.5 psia during the start transient and 5.5 psia for the remainder of the run (after 2.7 seconds).

Hot Run 17.01 was terminated after 1.39 seconds by a false turbine shutoff solenoid voltage (TSSV) abort. The abort was triggered by a voltage noise spike in the stand system. The data showed that, although engine ignition took place, chamber pressure was not rising to the required level. Therefore, the GOV preset was increased to 30 percent prior to the next run. Also, the Pc abort level after the start transient was decreased to 5.0 psia providing the engine with more latitude for operation.

Hot Run 18.01 was terminated by a low Pc abort 2.7 seconds after start. The data indicated that chamber pressure was again slow in rising. The abort sample time and pressure level were again adjusted to 3.1 sec and 5.0 psia respectively allowing a better chance for the engine to reach steady-state THI operation.

Hot Run 19.01 consisted of 146.2 seconds of THI run time. During the run fuel pump inlet pressure (FPIP) was increased to reduce the mixture ratio, which was high at start. While the GOV area was being decreased to further reduce the mixture ratio, the instability that was noticed on the nozzle exit video monitor prompted a manual abort. A post-test chamber/injector inspection revealed injector face discoloration and a small area of heat damage near the edge of the rigimesh. Figures 9 and 10 compare the injector face condition before the test series started and after H.R. 19.01. After reviewing the data, the instability noticed on the video monitor was determined not to be detrimental to engine operation.

Hot Run 20.01 was 11.1 seconds in duration. The run was terminated by a false rpm abort when an inaccurate signal was read by the computer system.

Hot Run 21.01 was a THI run with an attempt to transition to PI. Run duration was 356 seconds. During the THI portion of the run, fuel pump inlet pressure was decreased and the GOV area was varied until reasonably steady operating conditions were achieved. When the PI transition was attempted, an rpm overspeed abort terminated the run. Post-test data review indicated that although the data anomaly from the previous run had been corrected, the rpm signal was again erroneous. A suspected noisy pump speed sensor was replaced.

Hot Run 22.01 was a THI run with attempt to transition to PI; however, PI operation was prevented by a Pc/fuel pump discharge pressure (FPDP) abort 0.84 second after the transient signal. This calculated abort was triggered when data indicated that the engine turbopump was not accelerating properly. During THI engine operation appeared somewhat more unstable than the previous run although valve settings were essentially the same. Prior to the next PI transient attempt, the TBV opening time was delayed slightly to improve pump acceleration, and the CVV was closed to 35 percent instead of 20 percent to increase total fuel flow through the system.

TABLE 1. — XR201-2 TEST SUMMARY

Run No.	Date	Hot Time (sec) THI	PI	Total	Accumulated	Run Summary	Value Positions* — Percent of Full Open: THI GOV Initial/Final	THI CVV Initial/Final	THI TBV Initial/Final	PI GOV Initial/Final	PI CVV Initial/Final	PI TBV Initial Final
16.01	12-18-87	0.2	0.0	0.2	0.2	Had low chamber pressure abort during start transient	21/99	100/100	93/100	N/A	N/A	N/A
17.01	01-06-88	1.4	0.0	1.4	1.6	Had false turbine shutoff solenoid voltage abort during start transient.	22/22	100/100	91/91	N/A	N/A	N/A
18.01	01-06-88	2.7	0.0	2.7	4.3	Had low chamber pressure abort late in start transient.	32/32	100/100	90/90	N/A	N/A	N/A
19.01	01-06-88	146.1	0.0	146.1	150.4	Achieved THI start. Used fuel inlet pressure and GOV to reduce mixture ratio. Run was aborted when instability was observed on video.	32/23	100/100	90/90	N/A	N/A	N/A
20.01	01-07-88	11.1	0.0	11.1	161.5	Achieved THI start. Had false rpm abort early in run.	22/22	100/100	92/92	N/A	N/A	N/A
21.01	01-08-88	354.6	0.0	354.6	516.1	Achieved THI start. Performed inlet pressure and GOV excursions at THI. Had rpm overspeed abort during PI transient.	32/17	100/100	92/91	N/A	N/A	N/A
22.01	01-08-88	231.8	0.9	232.7	748.8	Achieved THI start. Reduced fuel inlet pressure and GOV area to stabilize engine and approach design conditions. Had P_c/FPDP abort during PI transient.	22/17	100/100	93/92	17/22	0/57	100/20
23.01	01-11-88	140.9	1.5	142.4	891.2	Achieved THI start. Reduced fuel inlet pressure and GOV area to stabilize engine. Had false P_c/FPDP abort during PI transient.	21/16	100/100	91/91	N/A	N/A	N/A
24.01	01-12-88	129.0	3.5	132.5	1023.7	Achieved THI start. Reduced fuel inlet pressure and GOV area to stabilize engine. Run was aborted due to duel pump discharge overpressure during PI transient.	21/16	100/100	92/91	16/36	0/52	36/36

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TABLE 1. — XR201-2 TEST SUMMARY (CONTINUED)

Run No.	Date	Hot Time (sec) THI	Hot Time (sec) PI	Hot Time (sec) Total	Hot Time (sec) Accumulated	Run Summary	Valve Positions* — Percent of Full Open: THI GOV Initial/Final	THI CVV Initial/Final	THI TBV Initial/Final	PI GOV Initial/Final	PI CVV Initial/Final	PI TBV Initial Final
25.01	01-12-88	117.7	0.1	117.8	1141.5	Achieved THI start. Reduced fuel inlet pressure and GOV area to stabilize engine. Run aborted when flameout occurred during transient.	22/17	100/100	92/91	17/17	0/32	100/100
26.01	01-13-88	83.2	0.0	83.2	1224.7	Achieved THI start. A flameout occurred during THI while the GOV area was being decreased. The OCV was removed prior to the run to determine the effects of excessive leakage.	22/17	100/100	92/92	N/A	N/A	N/A
27.01	01-13-88	254.3	4.1	258.4	1483.1	Achieved THI start. Reduced fuel inlet pressure and GOV area to stabilize engine. Had abort when capsule pressure momentarily rose above the abort level.	22/36	100/100	92/91	36/54	0/64	100/34
28.01	01-13-88	138.5	0.1	138.6	1621.7	Achieved THI start. Reduced fuel inlet pressure and GOV area to stabilize engine. Had flameout during PI transition.	22/36	100/100	91/91	36/35	0/64	99/86
29.01	01-14-88	126.5	6.3	132.8	1754.5	Achieved THI start. Reduced fuel inlet pressure and GOV area to stabilize engine. PI transition was achieved but run was aborted when chamber pressure oscillated below abort level.	22/36	100/100	91/91	36/55	0/66	100/38
30.01	01-14-88	130.9	3.5	134.4	1888.9	Achieved THI start. Reduced fuel inlet pressure and GOV area stabilize engine. A low chamber pressure abort occurred 3.6 sec into PI, probably due to insufficient total propellant flow.	22/37	100/100	91/91	37/63	0/64	100/21
31.01	01-15-88	125.3	303.9	429.2	2318.1	Achieved THI start. Reduced fuel inlet pressure and GOV area to stabilize engine. A transition to PI was made. TBV and CVV adjustments were made in attempt to reduce P_c and stabilize engine. Run was aborted after 304 sec of PI operation when P_c oscillated below abort level.	20/33	100/100	90/88	**	**	**

TABLE 1. — XR201-2 TEST SUMMARY (CONTINUED)

Run No.	Date	Hot Time (sec) THI	Hot Time (sec) PI	Hot Time (sec) Total	Hot Time (sec) Accumulated	Run Summary	Valve Positions* — Percent of Full Open THI GOV Initial/ Final	THI CVV Initial/ Final	THI TBV Initial/ Final	PI GOV Initial/ Final	PI CVV Initial/ Final	PI TBV Initial Final
32.01	01-15-88	101.4	482.1	583.5	2901.6	Achieved THI start. Reduced fuel inlet pressure and GOV area to stabilize engine. After the PI transition was made, the TBV, CVV, and oxidizer inlet pressure were adjusted in an effort to achieve stable operation, which was never reached. The engine was shut down when the stand steam supply was depleted.	20/34	100/100	90/89	33/92	0/82	100/20
33.01	01-19-88	3.1	0.0	3.1	2904.7	Prior to run, HHT heat exchanger was removed and LHT heat exchanger was installed. The run was aborted during the start transient by an erroneous chamber pressure abort.	22/22	100/100	94/94	N/A	N/A	N/A
34.01	01-19-88	369.4	0.0	369.4	3274.1	Achieved THI start. Adjusted fuel pump inlet pressure and GOV area to stabilize chamber pressure and approach design operating conditions. The engine was shut down before the PI transient due to a low liquid level in the stand LOX run tank.	23/42	100/100	93/93	N/A	N/A	N/A
		Σ = 2468.1	Σ = 806.0									

* — OCV always closed

* * — Not available due to data recording anomaly

N/A — Not Applicable

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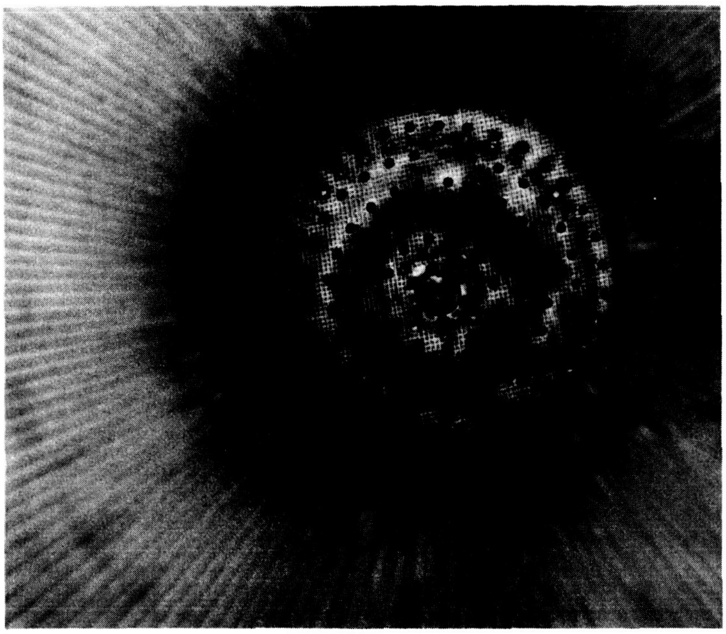

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Figure 9. RL10-IIB Engine XR201-2 Injector Face Prior to Hot Firings

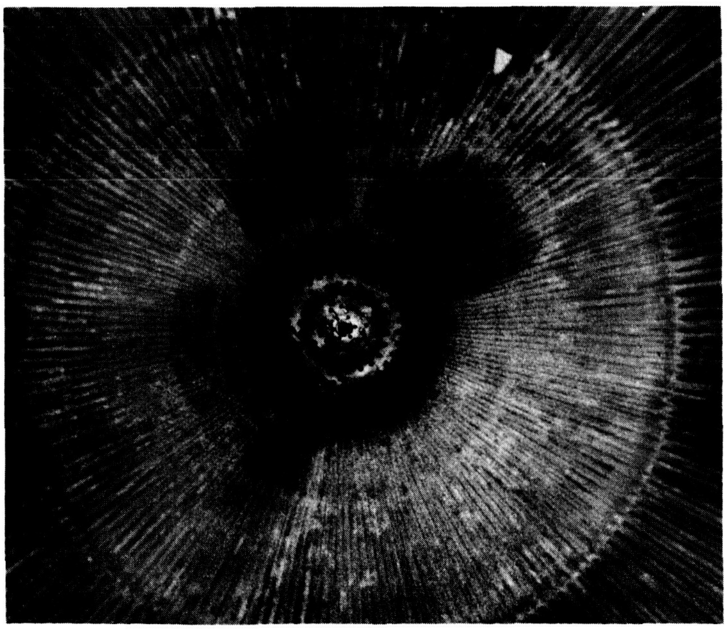

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Figure 10. RL10-IIB Engine XR201-2 Injector Face After Hot Run 19.01

Hot Run 23.01 lasted 142.4 seconds and aborted on a false Pc/FPDP abort at 1.5 seconds into the PI transient. A post-run review of the data indicated that a software aberration in the abort program was at fault. At this point the abort database was reevaluated and changed to improve the chances for a successful PI transient.

Hot Run 24.01 was aborted during the PI transient by a FPDP abort when the pump apparently oversped. The run lasted for 132.5 seconds. Prior to the next run, the TBV area was increased to 70 percent after the transient to attenuate the overspeed problem by reducing flow to the turbine.

Hot Run 25.01 was aborted during the PI transient due to a flameout in the chamber. The run duration was 117.8 seconds. Further investigation suggested that a possible problem existed with the stand electric control circuits; however, indications were intermittent and unrepeatable, making a positive determination difficult. For the next run, the CVV setting after the transient was changed back to 35 percent, and the GOV area was increased to 55 percent after the transient to provide more Pc back pressure. The OCV was removed from the oxidizer circuit and replaced with blankoff plates because data review from previous runs revealed the OCV may be leaking. Since the OCV serves no function during THI or PI operation other than to block oxidizer flow around the heat exchanger, the OCV was not needed for low thrust level runs. When needed for a full thrust run, the OCV could be reinstalled on the engine. The OCV may be providing a leak path into the injector for liquid oxygen (LOX), causing combustion instability.

Hot Run 26.01 verified the speculation that the OCV was leaking on previous runs. During the 83.2 second run without the OCV, engine operation was noticeably more stable as observed on the video monitor and in the post-test data. While the GOV area was being decreased, a flameout occurred when the mixture ratio decreased below the ignitable range. No changes were made to the run program prior to the next run.

Hot Run 27.01 was a 258.4 second run with 4.1 seconds at PI. At that time, the run was aborted by a high capsule pressure abort. Data review indicated that the abort was caused by a momentary pressure spike during the transient. The abort activation time was delayed for the next run. The TBV momentary closed time during the PI transient was decreased by 100 milliseconds to reduce the pressure overshoot.

Hot Run 28.01 was terminated by a flameout during the PI transient, apparently similar to the Hot Run 25.01 occurrence. The run was 138.6 seconds in duration. A more in-depth investigation revealed a delay in energizing the turbine shutoff valve solenoid, which was traced to a faulty test stand electrical circuit. The circuit was switched and a timing test verified the problem was rectified.

Hot Run 29.01 was a 132.7 second run that continued the effort to achieve the PI transition. A total of 6.3 seconds at PI were accumulated before the run was aborted when chamber pressure fell below the 35 psia abort level. The data showed a chamber pressure overshoot, after which it decreased rapidly to 38 psia. Oscillations then drove it below the abort limit. Since indications were that mixture ratio was far below the design point, valve settings were adjusted to increase oxygen flow and decrease fuel flow. Also, the chamber pressure abort level was decreased to provide more margin for operation.

Hot Run 30.01 was a 134.4 second run. A chamber pressure abort terminated the run 3.6 seconds into PI. The data indicated that the low chamber pressure was a result of insufficient total propellant flow. Both the GOV and the CVV ramps were changed to increase the flow area after the transient. The chamber pressure abort level was decreased further to provide additional margin for operation.

Hot Run 31.01 was made for 429.2 seconds, of which 125.3 seconds were at THI and 303.9 seconds were at PI. After the successful PI transition, operation at PI was unsteady and chamber pressure was significantly higher than design point. Chamber pressure was decreased by closing the CVV and oscillation amplitude was reduced somewhat by TBV and CVV adjustments; however, stable PI operation was never achieved. The run was terminated when chamber pressure oscillated below the 20 psia abort level.

Hot Run 32.01 was a 583.5 second run with 101.5 seconds at THI and 482.0 seconds at PI. The transient was made with the same valve settings used during the last run. During PI operation the TBV, CVV, and oxidizer inlet pressure were adjusted to reduce chamber pressure and locate areas of combustion stability. Increasing the TBV flow area appeared to steady the engine; however, stable operation was never achieved. The engine was shut down by the stand operator when the steam supply was depleted.

After Hot Run 32.01, the HHT heat exchanger was removed from the engine and the LHT unit was installed. The OCV remained off the engine.

The intent of Hot Run 33.01 was to demonstrate THI and PI operation with the LHT heat enchanger installed. The run was aborted 3.1 seconds after start by an erroneous chamber pressure abort. The abort, triggered as a result of the limited resolution of the abort database, was adjusted by decreasing the level for the next run.

Hot Run 34.01 was made for 370.3 seconds at THI. During that time, adjustments were made to the GOV area and fuel pump inlet pressure to approach engine and heat exchanger design conditions. Stable operation using the LHT heat exchanger was attained. The engine was shut down by the stand operator before the PI transient could be attempted due to a low liquid level in the LOX tank.

A planned final THI and PI run could not be performed due to a damaged fuel flowmeter discovered in the stand hydrogen run line. The integrity of the flowmeter could not be verified without complete removal, teardown, and inspection. As this would require a lengthy downtime and funds for the program were limited, no further runs were attempted and the engine was pulled from E-6 stand.

During the test series, cross-circuit leakage tests were performed on the heat exchanger to ensure structural degradation did not permit mixing of hydrogen and oxygen inside the heat exchanger during operation. This was accomplished by pressurizing the engine oxidizer circuit, isolating the heat exchanger hydrogen circuit, and measuring the leakage from the circuit. These tests were performed after each long duration hot firing. A 100-sccm gaseous nitrogen leakage limit was established. Neither heat exchanger exceeded this limit during the test series.

TEST RESULTS

Despite numerous operational and stand problems encountered during the test series, an extensive amount of THI runtime and a limited amount of PI runtime was accumulated on the HHT heat exchanger. Due to limited remaining test time available with the LHT heat exchanger installed, brief runtime was obtained at THI only. An opportunity to transition to PI, while the LHT heat exchanger was installed, did not occur.

Once proper abort levels were determined, the engine started and demonstrated stable operation at THI with the high heat transfer heat exchanger installed. Although fairly stable operation was achieved (Pc varying ± psia) during THI, some unstable flashes of light were evident in the diffuser. Intermittent and varying in intensity, the flashes did not correlate with minor Pc instabilities observed in the data. Although the cause of the observed flashes was never determined, when data indicated that liquid oxygen was leaking through the OCV, post-Hot Run 25.01 removal of the OCV decreased the intensity and frequency of the observed flashes considerably. THI performance with the low heat transfer heat exchanger installed was similar. An analysis of THI operation with each heat exchanger installed is present in Appendix C.

After successfully achieving the THI-to-PI transition, steady-state PI engine operation with the high heat transfer heat exchanger installed was unstable. Chamber pressure during initial PI operations averaged near 130 psia, far exceeding the required 40 psia for 10 percent thrust operation. At this level, chamber pressure oscillations of ± 20 psid were present with a frequency of approximately 2 cycles/second. Hydraulic valve adjustments reduced the Pc levels, but stable operation could not be reached as propellant flowrates were never reduced to heat exchanger design levels. A complete analysis of PI operation with the high heat transfer heat exchanger installed is present in Appendix C.

Conclusions

The test program results provide the following conclusions:

1. Stable THI engine operation was achieved with either heat exchanger installed. Further exploration of propellant flow and pressure adjustments may improve this level of stability.

2. Pumped idle engine operation with the HHT heat exchanger was largely unstable. This may not necessarily be due to inherent heat exchanger instability, as propellants were never supplied to the heat exchanger at design conditions. Attempts to reduce the fuel flow to approach design levels tended to increase the level of instability.

3. The two heat exchanger designs were indistinguishable in performance at THI. A comparison could not be made for PI operation.

4. Pumped idle engine operation during testing with the HHT heat exchanger installed was near 25 percent of full thrust rather than the 10 percent design point.

5. The heat exchangers did not suffer any structural degradation in the form of cross-circuit propellant leakage as a result of engine thermal cycles.

Recommendations

The following recommendations are made based on the test program results, data analysis, and conclusions:

1. Further engine testing is necessary to define performance of the heat exchangers at PI. Proper characterization cannot be accomplished unless propellant flowrates are reduced to 10 percent design point thrust levels, where ranges of stability are present as indicated by the heat exchanger component testing described in Reference 3.

2. Additional engine testing could refine THI operation through further hydraulic valve setting adjustments.

3. Should further testing determine that no areas of stability can be located near the THI design point, some level of active control may be necessary to successfully manage propellants entering the injector.

REFERENCES

1. Breadboard RL10-IIB Low Thrust Operating Mode Final Test Report. P&W Report No. FR-18683-2, NASA Report No. CR-174914, January 1987.

2. Design and Analysis Report for the RL10-IIB Breadboard Low Thrust Engine. P&W Report No. FR-18046-3, NASA Report No. CR-174857, 12 December 1984.

3. Oxidizer Heat Exchanger Component Test Report. P&W Report No. FR-19602, NASA Report No. CR-182159, November 1987.

4. High Heat Transfer Oxidizer Heat Exchanger Design and Analysis Report. P&W Report No. FR-19289-1, NASA Report No. CR-179596, May 1987.

5. Low Heat Transfer Oxidizer Heat Exchanger Design and Analysis Report. P&W Report No. FR-19135-2, NASA Report No. CR-179488, 30 January 1987.

APPENDIX A
COMPONENT AND ENGINE CONFIGURATION

All engine components (except heat exchangers) were obtained from engines used during RL10 low thrust testing which was conducted during 1984. The following sections describe the components used in the buildup of the breadboard RL10-IIB demonstrator engine XR201-1, Build 2.

FUEL PUMP AND TURBINE ASSEMBLY

The fuel pump and turbine were received intact from XR201, Build 1. This assembly was baseline RL10A-3-3A except for the following:

1. A new gear was provided to increase the oxidizer pump speed. The shaft assembly was obtained by installing the new gear onto an existing shaft. The gear ratio (fuel pump to oxidizer pump) was changed from 2.500:1 for RL10A-3-3A Bill-of-Material (B/M) to 2.118:1.

2. The lower 1st-turbine stator flow area was obtained by installing 10 additional plugs into a reduced area stator. This stator had an area reduction of 10 percent from the RL10A-3-3A B/M prior to installing the plugs. Water flows on G-13 test bench showed an effective area of 1.072 in.^{2} or a total reduction of 22 percent from the RL10A-3-3A B/M.

3. The second stator also had a reduced area. This stator was obtained from development engine FX141-45, which was built as an RL10A-3-7 in 1966, and had an effective area of 1.471 in.^{2} versus 1.9 in.^{2} for the RL10A-3-3A.

4. The exit stator was also from FX141-45 and included a cone shaped exit shroud designed to reduce the discharge housing pressure losses.

Turbopump build, rotor balance, pressure test, and seal flows were accomplished per standard RL10 procedures during Build 1.

OXIDIZER PUMP AND GEARBOX ASSEMBLY

The oxidizer pump and gearbox assembly were baseline RL10A-3-3A with most parts obtained from XR201, Build 1. The following describes the major differences:

1. A new gear was incorporated to provide the 2.118:1 gear ratio. An existing shaft was utilized, a new gear installed, and the bearing seat machined. This shaft assembly also incorporated a short accessory drive coupling to allow installation of a speed transducer at the accessory pad.

2. A single bearing idler gear was used per layout L-238361. The new gear was required to incorporate the ratio change. The single bearing feature, tested during the 1960s, was used to reduce gear wear due to housing misalignment. A new bearing was installed during Build 2.

3. The elbow housing was modified to accept the single bearing configuration and the 2.118:1 idler gear.

The oxidizer pump was built and seals were flow tested per standard RL10 procedures during Build 1.

FUEL VENT VALVE

The fuel vent valve (FVV) is based on the RL10A-3-3A pump discharge cooldown valve (PDCV). The only purpose of this valve, however, is to provide venting of fuel following engine shutdown. The valve ports are enlarged to provide additional flow area, since there is no interstage cooldown valve (ICV). The effective vent flow area for this valve is 0.510 in.^{2}, compared to 0.300 in.^{2} for the RL10A-3-3A valve. Because the valve is required to open rapidly at shutdown from any thrust level, the signal pressure for opening is provided by helium, rather than hydrogen from the fuel pump discharge. This latter pressure would be insufficient to provide the required boost at tank head idle or pumped idle (THI) shutdown. This valve was obtained from engine XR201-1. A calibration was performed on this valve prior to the XR201-1 test series; therefore, a new calibration was not performed.

TURBINE BYPASS VALVE

The turbine bypass valve (TBV) was obtained from XR201-1. Prior to installation on the engine, a restriction in valve movement was discovered. The valve gate was removed, and an interference between the gate and housing was found. The interference was corrected and the valve was cleaned, reassembled, and installed on the engine. A gaseous nitrogen flow calibration was performed prior to the XR201-1 test series; therefore, no new calibration was performed. The effective area versus valve position is shown in Figure A-1.

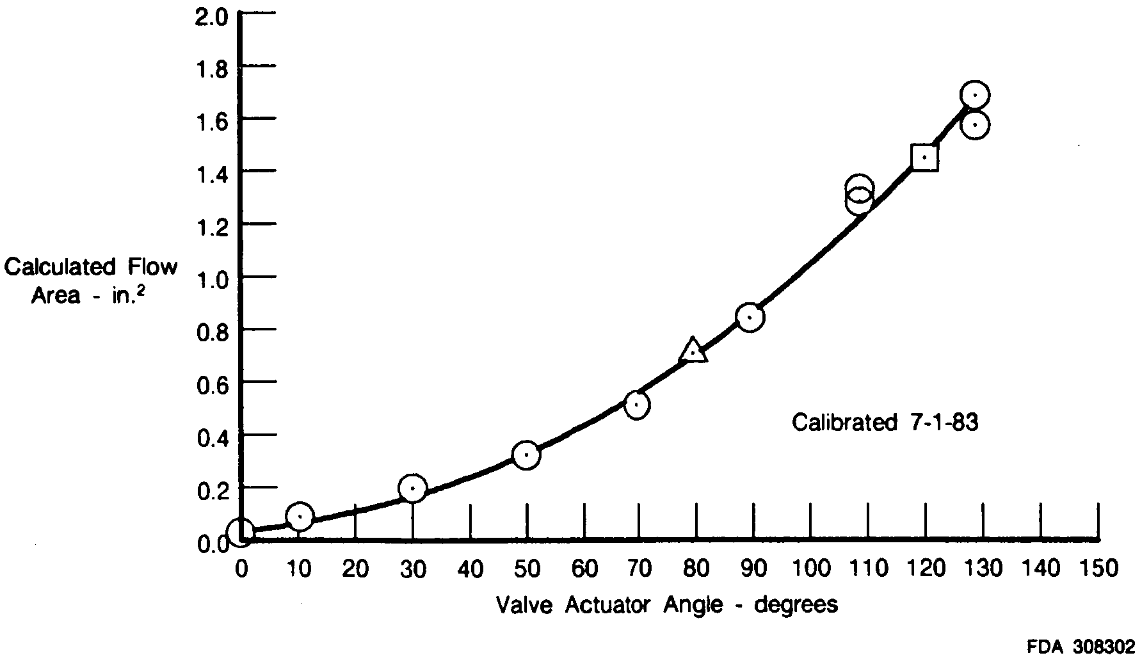

Figure A-1. Turbine Bypass Valve S/N CKD 1188 Calibration

OXIDIZER CONTROL VALVE

The Oxidizer Control Valve (OCV) was obtained from XR201-1. This valve was cleaned and a liquid nitrogen calibration was performed on G-1 test stand prior to the XR201-1 test series; therefore, no new calibration was performed. The effective area versus valve position is shown in Figure A-2.

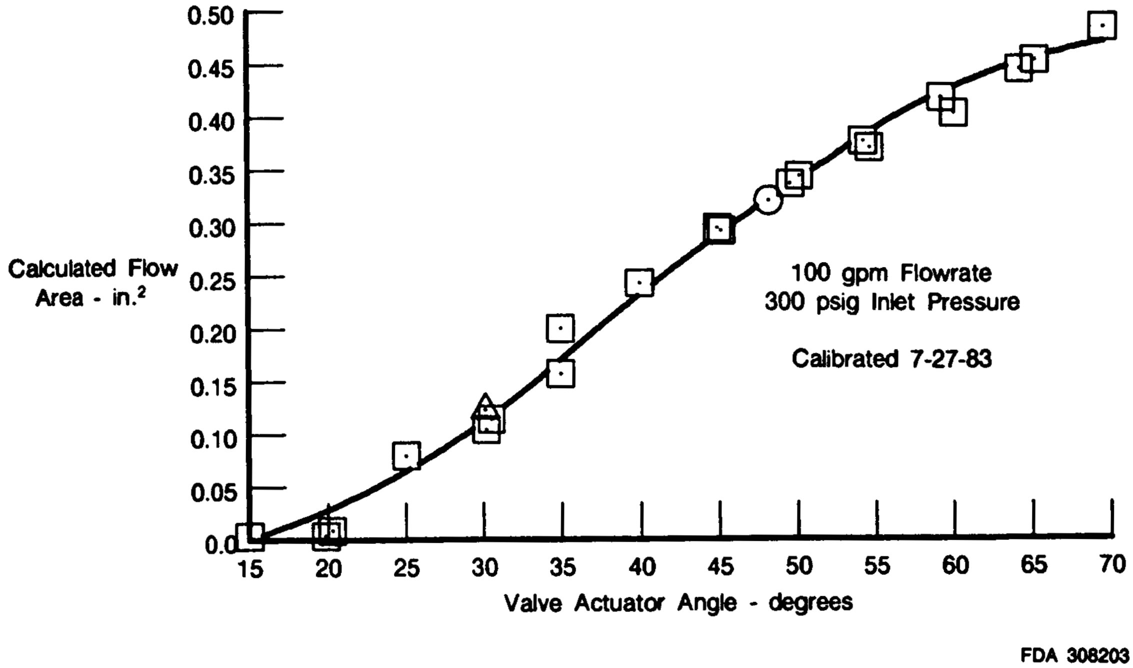

Figure A-2. Oxidizer Control Valve S/N 600090 Calibration

CAVITATING VENTURI VALVE

The Cavitating Venturi Valve (CVV) was obtained from XR201-1. Calibration data from 1967 was available; therefore, no new calibration was performed. The effective area versus valve position is shown in Figure A-3.

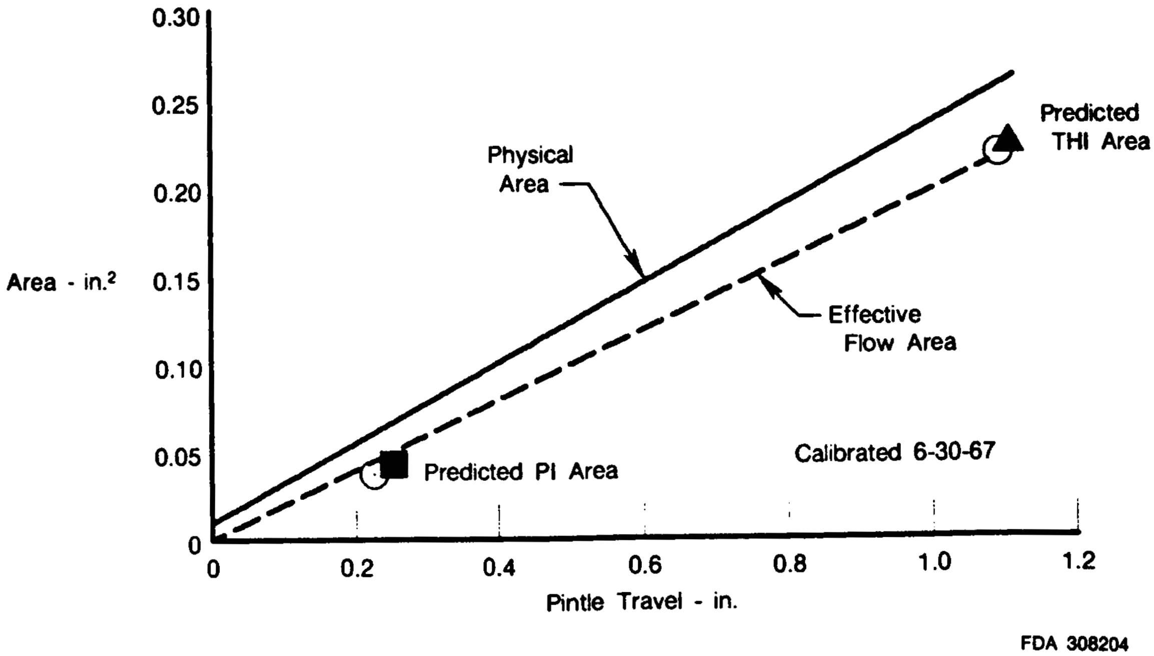

Figure A-3. Cavitating Venturi S/N B54X-012 Calibration

GASEOUS OXIDIZER VALVE

The Gaseous Oxidizer Valve (GOV), was obtained from XR201-1. Calibration curves were available for this valve; therefore, a new calibration was not performed. The effective area versus valve position curve that was used is shown in Figure A-4.

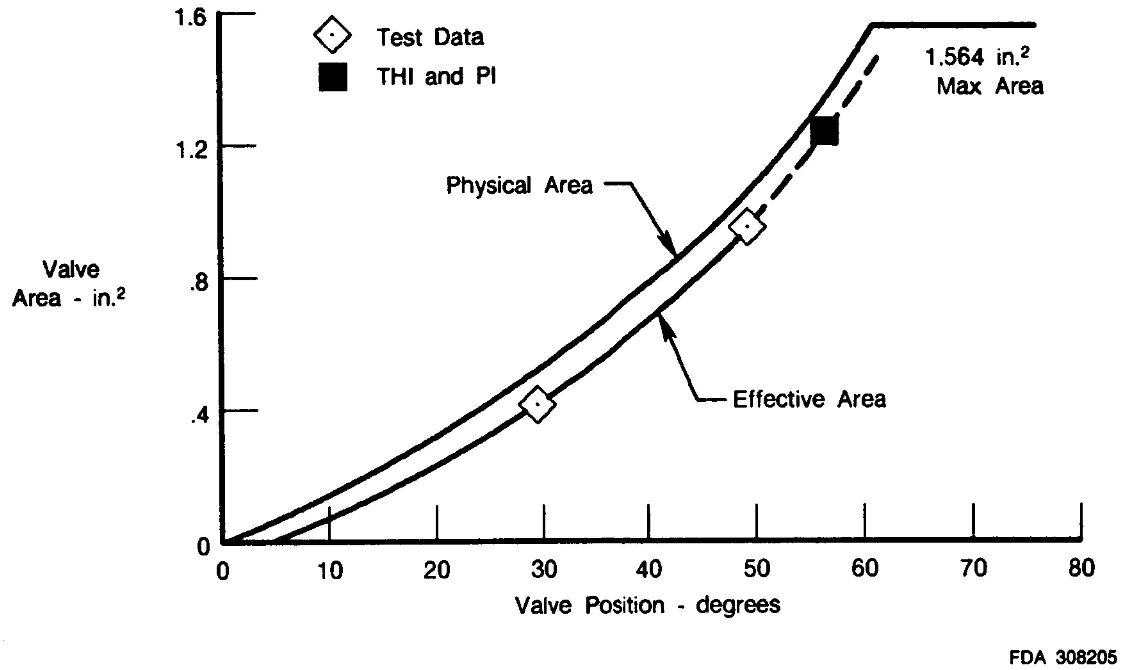

Figure A-4. Gaseous Oxidizer Valve S/N CKD 1311 Calibration

IGNITION SYSTEM

The system used to ignite the propellants consisted of two spark ignition systems, each similar to that used for the RL10A-3-3A integrated with a torch igniter housing. Hydrogen and oxygen are supplied to the torch igniter housing and this mixture is then ignited by the spark igniters. The resulting "torch" then ignites the propellants in the combustion chamber. The spark ignition systems and torch igniter housing were obtained from engine XR201-1. This system was developed in the 1960s to provide reliability as well as redundancy for safe, repeatable propellant ignition in the combustion chamber.

CHAMBER

The purpose of the hook tube design is to reduce potential tube socket leaks by locating the joints away from the combustion area. This is the same joint design that will be used for the new thrust chamber/primary nozzle for the RL10-IIB. The difference between this joint design and the RL10A-3-3A is shown in Figure A-5. Obtained from XR201-1 and similar to the RL10A-3-3A chamber, the thrust chamber/primary nozzle assembly has no silver throat and incorporates a hook tube exit manifold.

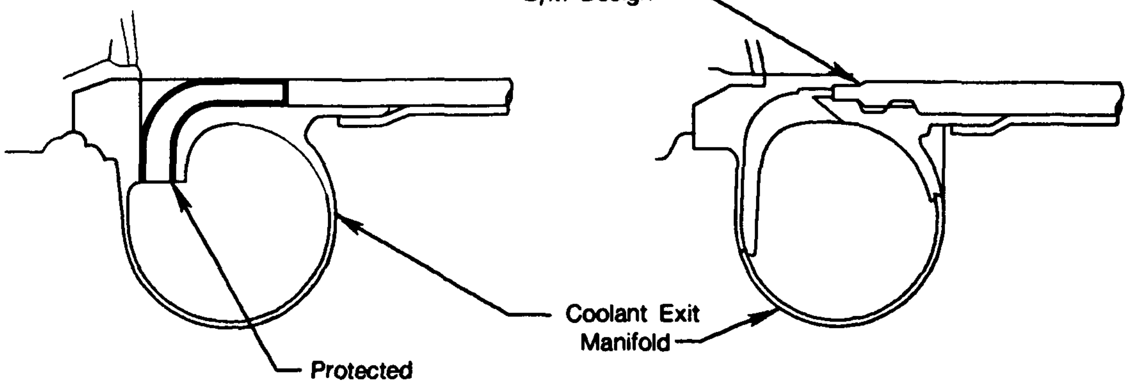

Figure A-5. Thrust Chamber Exit Manifold Differences

INJECTOR

The injector for this build was obtained from XR201-1 and was modified to accept a torch igniter. The remainder of the injector was baseline RL10A-3-3A with 120 scfm flow rigimesh on the faceplate. The injector also had a provision for installation of a flame detector probe. Data from previous engine runs indicated an effective area of 0.7550 in.^{2} for the oxidizer side and 2.361 in.^{2} for the fuel side.

THRUST CONTROL

Because the RL10A-3-3A configuration thrust control was not required to be functional for the THI and PI thrust levels, neither a chamber pressure sensing line nor the restrictor assembly was connected to the engine. A line from turbine upstream pressure was connected to the servo supply fitting to prevent any differential pressure across the bypass valve, thus allowing the internal spring to keep the valve closed during engine operation.

MISCELLANEOUS COMPONENTS

The solenoid valves, shutoff valves, and inlet valves were all RL10A-3-3A configuration. All completed calibrations prior to the XR201-1 engine test series except for the fuel inlet valve which was obtained from another engine. A prelaunch cooldown valve was installed on the engine, but was used only to provide a path for coolant flow from the fuel pump to the gearbox during engine operation.

PLUMBING

Plumbing from engine XR201-1 was used where possible. New large plumbing was fabricated by welding existing flanges to custom bent hydrogen and oxygen tubes. All new welds were X-rayed and fluorescent penetrant inspected. All new tubes were pressure checked to 1000 psig.

HYDRAULIC ACTUATORS

Hydraulic actuators were installed to control the position of the four breadboard valves. The actuators included linear position pots to supply a signal for the control system. Brackets for the TBV, OCV, GOV, and CVV were obtained from engine XR201-1.

GIMBAL

The gimbal was obtained from XR201-1 and included bracketing to allow mounting of the two spark ignition systems.

OXIDIZER HEAT EXCHANGER

Two different heat exchanger designs were tested. The first unit installed on the engine was a high heat transfer design manufactured by Alpha United, Incorporated. The second unit was a low heat transfer unit made by United Aircraft Products, Incorporated, which was installed later in the test series. A description of each configuration is provided in Appendix B.

APPENDIX B
HEAT EXCHANGER CONFIGURATIONS

GENERAL

As a second iteration of the RL10-IIB Demonstrator Engine Development Program, oxidizer heat exchanger designs were solicited from leading manufacturers of heat transfer equipment. Two responses resulted in the design and fabrication of heat exchanger prototype units employing two different design approaches. One design utilizes a high heat transfer rate within a compact core to vaporize the liquid oxygen, while a low heat transfer rate over a larger core area characterizes the second design. Performance tests, performed at the component level in 1986, verified each design concept as described in Reference 3. The tests revealed each heat exchanger design to be effective at the propellant conditions normally provided by the engine.

HIGH HEAT TRANSFER OHE

The HHT OHE is a single, self-contained unit encompassing a cross-counterflow, plate fin core within a tank shaped volume. All aluminum construction minimizes weight, while retaining favorable heat transfer characteristics. A schematic of the internal configuration with external dimensions is shown in Figure B-1. Liquid oxygen (LOX) enters through the bottom inlet flange and flows through a bellows into the core, where it absorbs heat from the adjacent hydrogen passages. The oxygen discharges into a volume, and exits the OHE through the discharge flange. The hydrogen enters through the inlet flange and flows through a manifold into Stage 2 of the core. It then proceeds through a turnaround manifold into Stage 1, discharges into the hydrogen half of the volume, and exits the OHE through the discharge flange. A complete description of the HHT OHE is provided in Reference 4. Figure B-2 presents a photograph of the HHT OHE.

The oxygen discharge volume serves to attenuate flow oscillations by providing a damping area for pulsing expansion of gases formed by violently boiling liquid. These pulses are further reduced by the oxygen discharge flange, which serves as an attenuating orifice to the pulsing oxygen. The hydrogen volume, which is separated from the oxygen volume by a dividing plate, serves no attenuating function; it merely acts as a manifold to collect the hydrogen prior to discharge. The core is suspended within the volume by the dividing plate. Since the core is completely contained within the volume, it does not sustain the full proof pressure, resulting in a lower strength requirement with its associated weight savings.

Each high heat transfer OHE was identified as P/N P-10770 and was designed and manufactured by Alpha United, Incorporated to comply with the requirements of Purchase Performance Specification (PPS) F-654. The engine-tested unit was S/N 002. The approximate dry weight was 32 pounds.

LOW HEAT TRANSFER OHE

The LHT OHE is a single, self-contained aluminum unit with a three-stage, plate fin core of cross-counterflow configuration designed to satisfy the requirments of PPS F-654. Figure B-3 presents a schematic of the heat exchanger with external dimensions. LOX enters through the bottom inlet flange and progresses through a manifold to the core. As the oxygen passes through stages 1, 2, and 3 of the core in a straight line, it vaporizes and exits through the discharge manifold and flange. The hydrogen enters through the inlet flange and manifold and enters stage 3 of the core. After passing through stages 3, 2, and 1 in succession, the hydrogen discharges through the exit manifold and flange. A more detailed description of the low heat transfer OHE can be found in Reference 5. A photograph of this OHE is shown in Figure B-4.

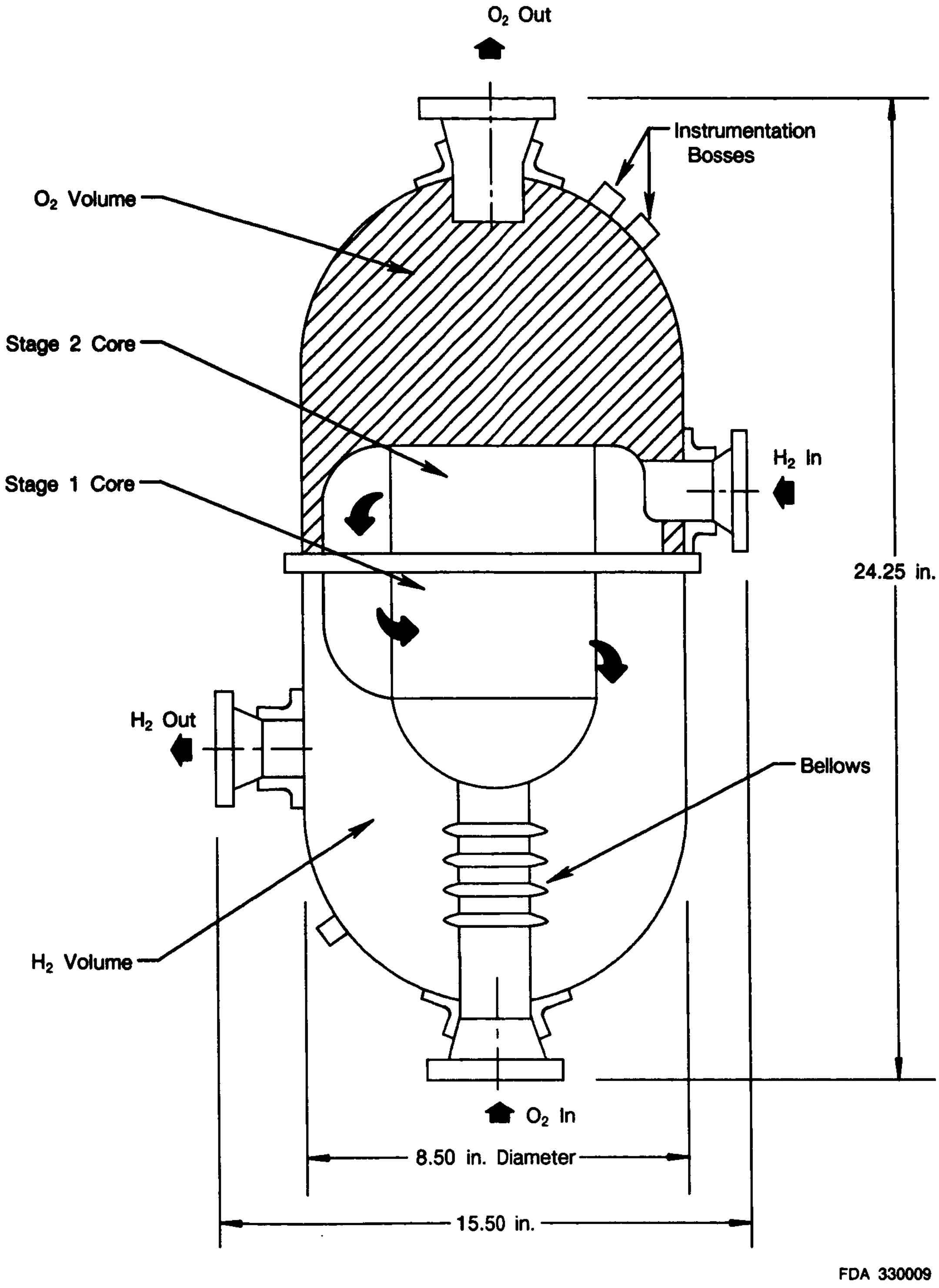

Figure B-1. High Heat Transfer Oxidizer Heat Exchanger Schematic

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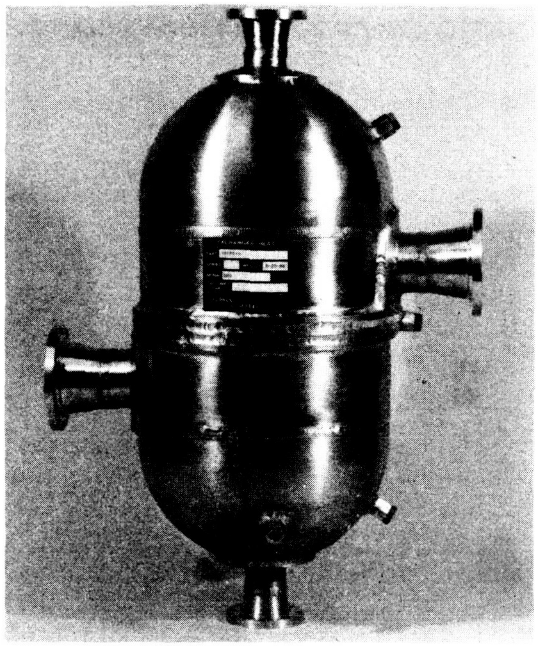
OF POOR QUALITY



FC 104112-H

Figure B-2. High Heat Transfer Oxidizer Heat Exchanger

To prevent violent oxygen boiloff and the associated flow instability, this heat exchanger uses a low heat flux over a large heat transfer area for gradual rather than rapid vaporization. Excessive heat transfer is prevented through the use of a resistance layer between the oxygen and hydrogen flow layers. This resistance layer is vented to vacuum, providing a thermal barrier to heat flow from the hydrogen to the oxygen.

Each LHT OHE was identified as P/N UA538949-1 CKD10001 and was manufactured by United Aircraft Products, Incorporated. The engine tested unit was S/N UAP R0002. The approximate dry weight was 64 pounds.

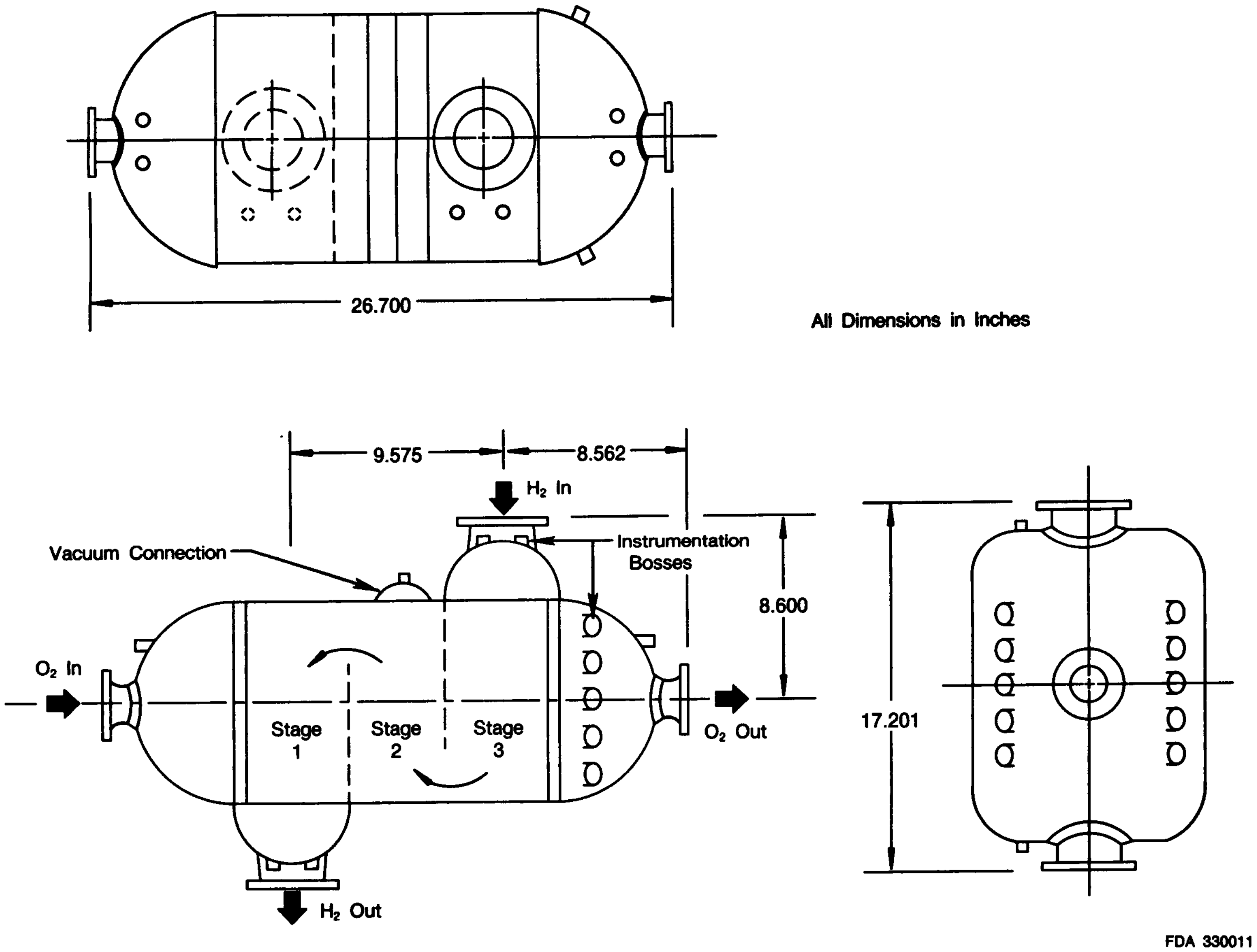
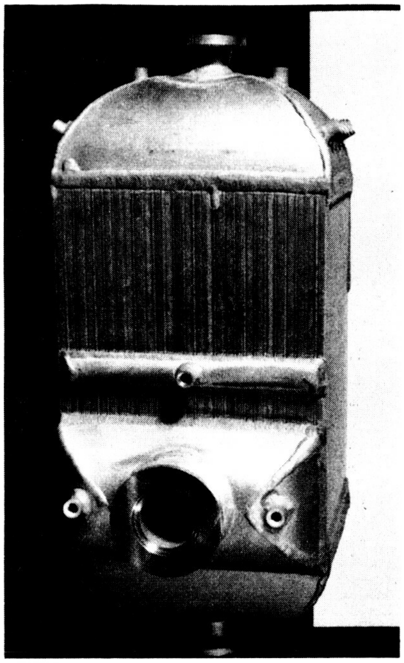


Figure B-3. Low Heat Transfer Oxidizer Heat Exchanger Schematic



FC 104113-H

Figure B-4. Low Heat Transfer Oxidizer Heat Exchanger

APPENDIX C
ENGINE PERFORMANCE ANALYSIS

To:	Don Galler
From:	Pia Watkins and Ray Kaldor
Subject:	Low Thrust Operation of RL10 with an Oxygen/Hydrogen Heat Exchanger Engine XR201-02
References:	1. High Heat Transfer Oxidizer Heat Exchanger Design and Analysis, FR-19289-1, 1-30-87
	2: Low Heat Transfer Oxidizer Heat Exchanger Design and Analysis Report Draft, FR-19135-1, 4-2-86
Date:	April 27, 1988
CC:	Jim Brown, Bob Foust, Paul Kanic, Bob Marable, Richard Wright, File

SUMMARY

Engine XR201-2 completed 19 hot firings totaling 3274.1 seconds in support of the RL10 Derivative IIB Low Thrust program. During runs 16.01 to 32.01, the engine accumulated 2095.6 seconds of tank head idle (THI) operation and 806.0 seconds of pumped idle (PI) operation with the high heat transfer heat exchanger (HEX) designed by Alpha United (Reference 4). The United Aircraft Products designed low heat transfer HEX (Reference 5) accumulated 372.5 seconds of THI operation. Heat transfer and pressure stability characteristics were analyzed for both HEX units and compared to design table values.

CONCLUSIONS

The engine can be successfully started and stably operated in the THI mode. Pump cooldown was accomplished in an average time of 50 sec. for the fuel pump and 110 sec. for the oxidizer pump. The transition from THI to PI operation was successfully demonstrated even though the steady state 10% thrust level was not achieved.

The Alpha United, Inc. high heat transfer HEX design demonstrated stable THI operation, producing gaseous oxygen at the injector manifold. PI operation was unstable, but the engine conditions achieved did not represent the 10% thrust level design point.

The United Aircraft Products low heat transfer HEX design demonstrated stable THI operation during its only test, yielding gaseous oxygen at the injector inlet. PI operation was not attempted with this HEX due to test program time constraints.

Ray Kaldor

Pia Watkins, Ext. 5351
Propulsion System Analysis

Ray Kaldor, Ext. 3722
Propulsion System Analysis

/kbd

P&W EDS 20000A Rev 2/85

Engine Configuration

XR201-2 incorporated the turbopump assembly, injector (S/N ACG 977) from XR102-1A, and chamber (S/N ACB 905) from XR201 Build 1. In addition, the hydraulic valves for the turbine bypass (TBV), the gaseous oxidizer (GOV), and the cavitating venturi (CVV) were retained from Build 1 as well as the turbine shutoff solenoid valve (TSSV). The high heat transfer HEX, designed by Alphs United, Inc., was installed during Runs 16.01 to 32.01 while the low heat transfer HEX, designed by United Aircraft Products was used for Runs 33.01 and 34.01. A summary of the engine tests made is given in Table C-1.

DISCUSSION

Engine Start and THI Steady State

During the initial phase of the test program, some difficulty was encountered in achieving engine start due to conservatism in setting engine abort limits used to protect both the test article and facility. This conservatism was brought about due to uncertainty of the engine ignition characteristics with the new HEX installed as well as a different location for the igniter fuel source. As experience was gained, these abort limits were changed and a successful start was achieved for Run 19.01. The valve settings and inlet pressure levels used to start the engine are listed in Table C-1. The pump cooldown characteristics are shown in Figure C-1 for the oxidizer pump and in Figure C-2 for the fuel pump.

Following pump cooldown, stable THI steady state operation was achieved by changing the GOV setting from 20% to 15%. Figure C-3 presents the THI steady state chamber pressure characteristics for both heat exchangers. Prior to run 26.01, the oxygen fluid conditions at the injector inlet were calculated to be two phase even though gaseous oxygen was measured at the HEX exit. The OFC valve was discovered to be leaking liquid oxygen directly to the injector. Since, during THI operation, the propellants flowrates are calculated using a gaseous flow equation (Attachment C-1) at the injector the oxygen flowrate cannot be determined with certainty for runs 16.01 — 25.01. Following run 25.01, the OCV valve was capped off and gaseous oxidizer flow was calculated at the injector.

THI heat transfer and pressure loss characteristics were determined for the Alphs United HEX for runs 26.01 — 31.01 and are presented in Table C-2. Oxygen side heat transfer is consistently lower than the hydrogen side heat transfer but is sufficient to produce gaseous oxidizer at the injector.

The United Aircraft Products HEX was installed for only one test. The THI heat transfer and pressure loss characteristics are also given in Table C-2 for two time slices. The oxygen side and hydrogen side heat transfers agree reasonably well and gaseous oxidizer was measured at the injector manifold. Both heat exchangers THI performance are compared to design point levels in Table C-3.

Transition to PI and PI Steady State

The engine was successfully transitioned to PI operation using a valve sequencing as shown in Figure C-4 and without using the overboard fuel vent valve which was required during Build 1 testing. Chamber pressure and turbine inlet temperature characteristics in going from THI to PI are shown in Figure C-5 for run 32.01. Although the PI transient was accomplished, the 10% thrust level was not achieved and engine performance could not be determined due to the instability of chamber pressure and flowrates. These oscillations were caused by the heat exchangers operating far from their design conditions (Table C-4). During run 32.01, chamber pressure was brought down to approximately 50% above the design valve of 40 psia. Heat transfer and pressure loss characteristics were calculated at this point for the Alphs United HEX and is shown in Table C-2.

Transition to PI was not attempted with the United Aircraft Products HEX due to low LOX tank levels and constraints on the test program. Chamber pressure and flowrate characteristics for PI operation are shown in Figures C-6 and C-7 for run 32.01.

FLOW CALCULATIONS

The Injector Flow calculation is:

$$\frac{w\sqrt{T}}{ACD(P)}\sqrt{\frac{g}{R}} = \sqrt{\frac{2\gamma}{\gamma - 1}\left[\left(\frac{P}{Pc}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}\quad\left(\frac{P}{Pc}\right)^{\frac{\gamma-1}{2\gamma}}$$

where:

	Pc	-Chamber pressure - psia
	P	-Inlet pressure - psia
	T	-Injector inlet temperature - deg R
	ACD	-Injector area sq. ins.
	g	-gravitational constant 32.174 ft/sec^2
	γ	-gamma (1.4)
	w	-flow rate - lb/sec (at the injector)
	R	-gas constant - (ft*lbf)/(lbm*deg R)

The Flow Meter calculation is:

$$W \rho / 448.8 = w$$

where:

	W	-flow meter flow rate - gal/min
	ρ	-density - lbs/ft^3 at the temperature and pressure at the flow meter
	w	-flow rate lbs/sec (at the flow meter)

The calculated injector fuel and lox flow for PI (Run 32.01) is 1.586 lb/sec and 3.829 lb/sec respectively. These values are obtained from the one second averages in the post test data printout, four hundred and forty eight seconds into PI. The corresponding flow meter calculations are 1.2696 lbs/sec fuel and 4.351 lbs/sec lox. These values translate to a fuel flow meter calculation that is 80% of the injector calculation and the lox injector calculation is 52% of the flow meter flow calculation at that point in the run. Figures 10 and 11 show the effect of each flow calculation on the 482 second run at PI. The injector calculation uses a fixed gamma of 1.4, this value was varied and the effect was negligible. The injector flow calculation is a steady state equation with ideal gas assumptions (no boundary layer effects, viscosity or inertia considerations) and is therefore not accurate to calculate flows under conditions of oscillating pressures and temperatures or when liquid is present.

The dump lines were open at PI during run 31.01. The dump lines were closed as scheduled in run 32.01. The difference between the injector and the flow meter flow calculations during run 32.01 could be caused from a leak in the fuel dump line or inaccuracies in the injector calculation.

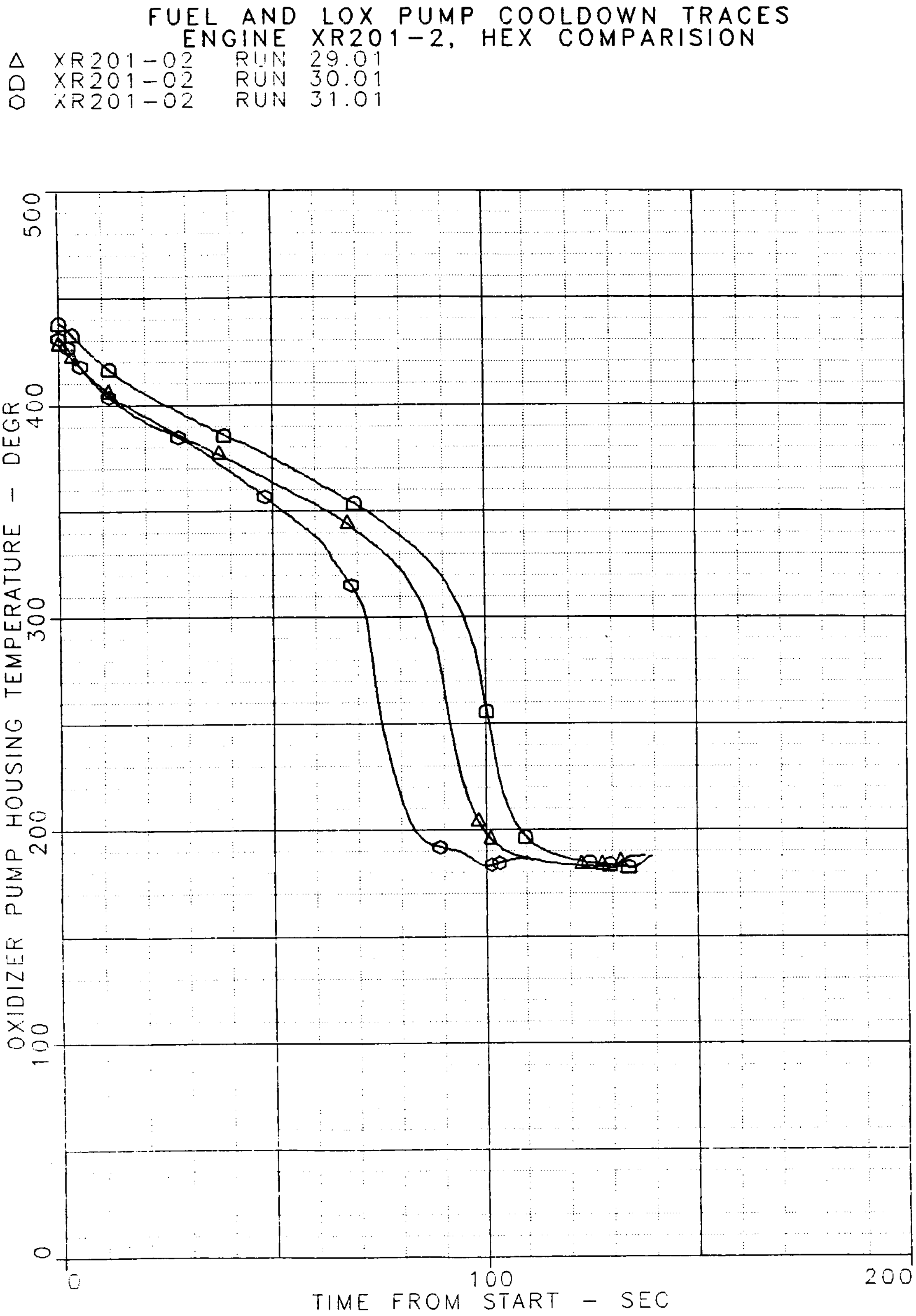
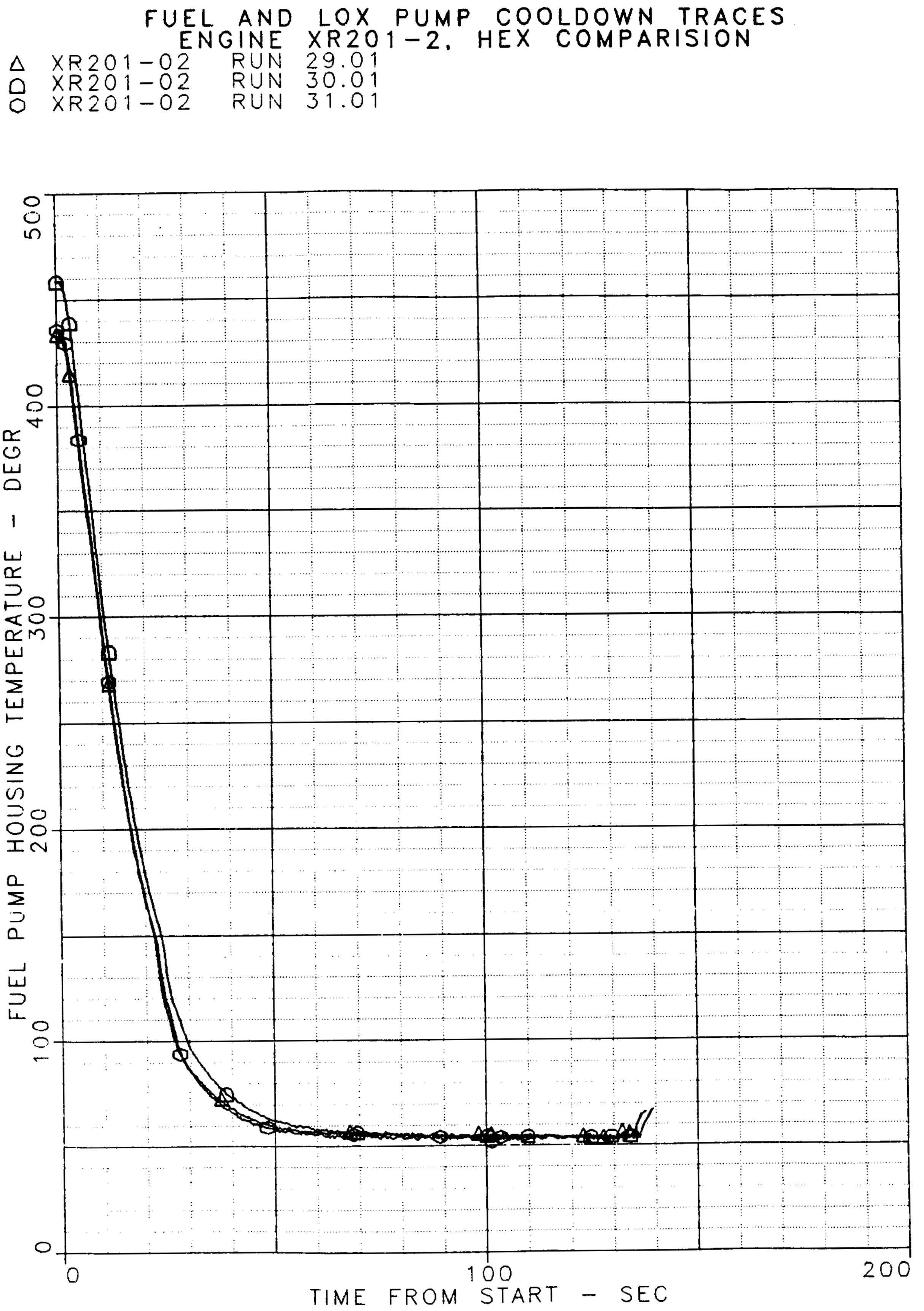

FUEL AND LOX PUMP COOLDOWN TRACES
ENGINE XR201-2, HEX COMPARISION
△ XR201-02 RUN 29.01
□ XR201-02 RUN 30.01
○ XR201-02 RUN 31.01
OXIDIZER PUMP HOUSING TEMPERATURE - DEGR
0
100
200
300
400
500
0
100
200
TIME FROM START - SEC

Figure C-1.



FUEL AND LOX PUMP COOLDOWN TRACES
ENGINE XR201-2, HEX COMPARISION
XR201-02 RUN 29.01
XR201-02 RUN 30.01
XR201-02 RUN 31.01
FUEL PUMP HOUSING TEMPERATURE - DEGR
0
100
200
300
400
500
0
100
200
TIME FROM START - SEC

Figure C-2.

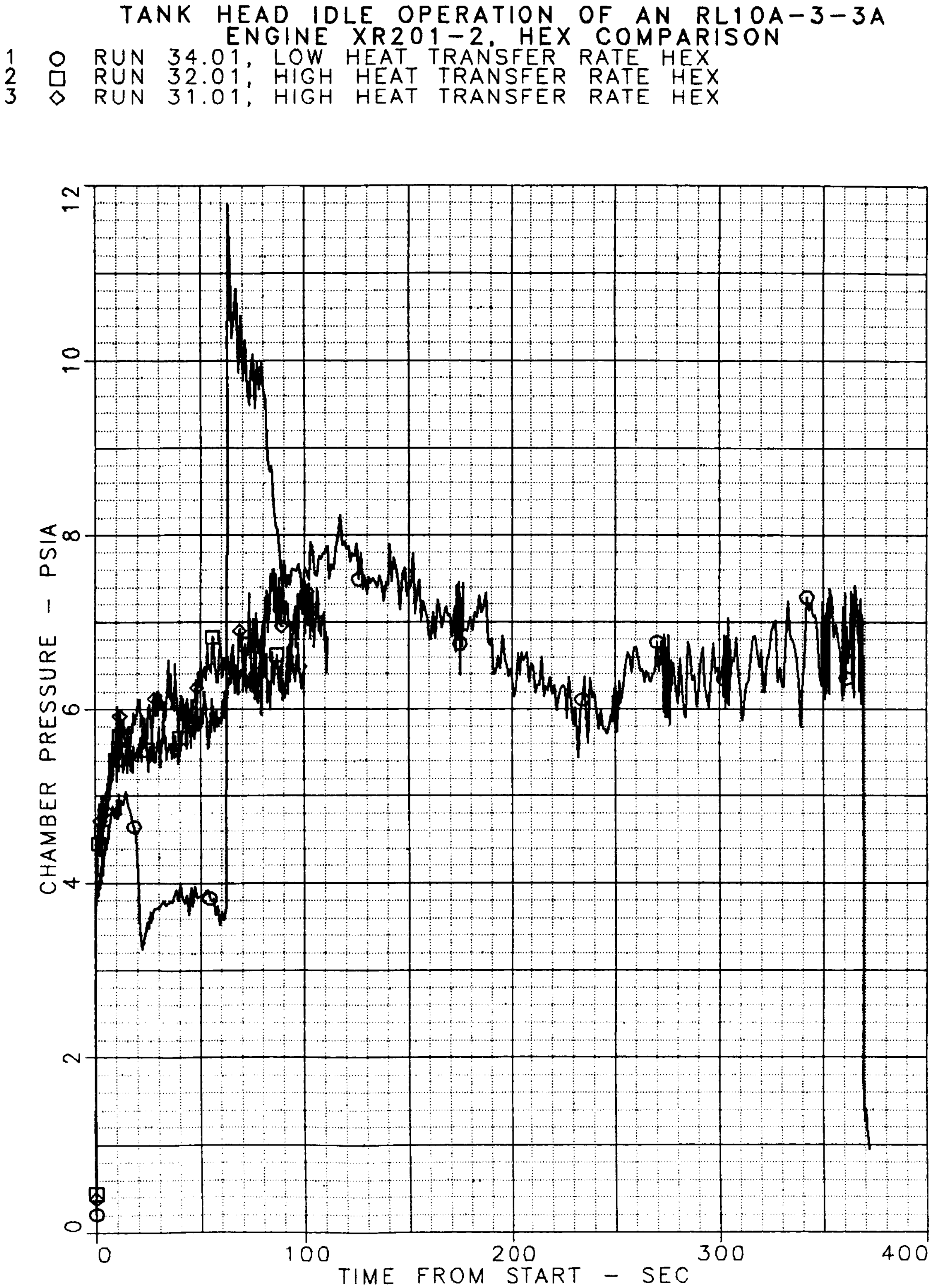


Figure C-3.

R182160/8

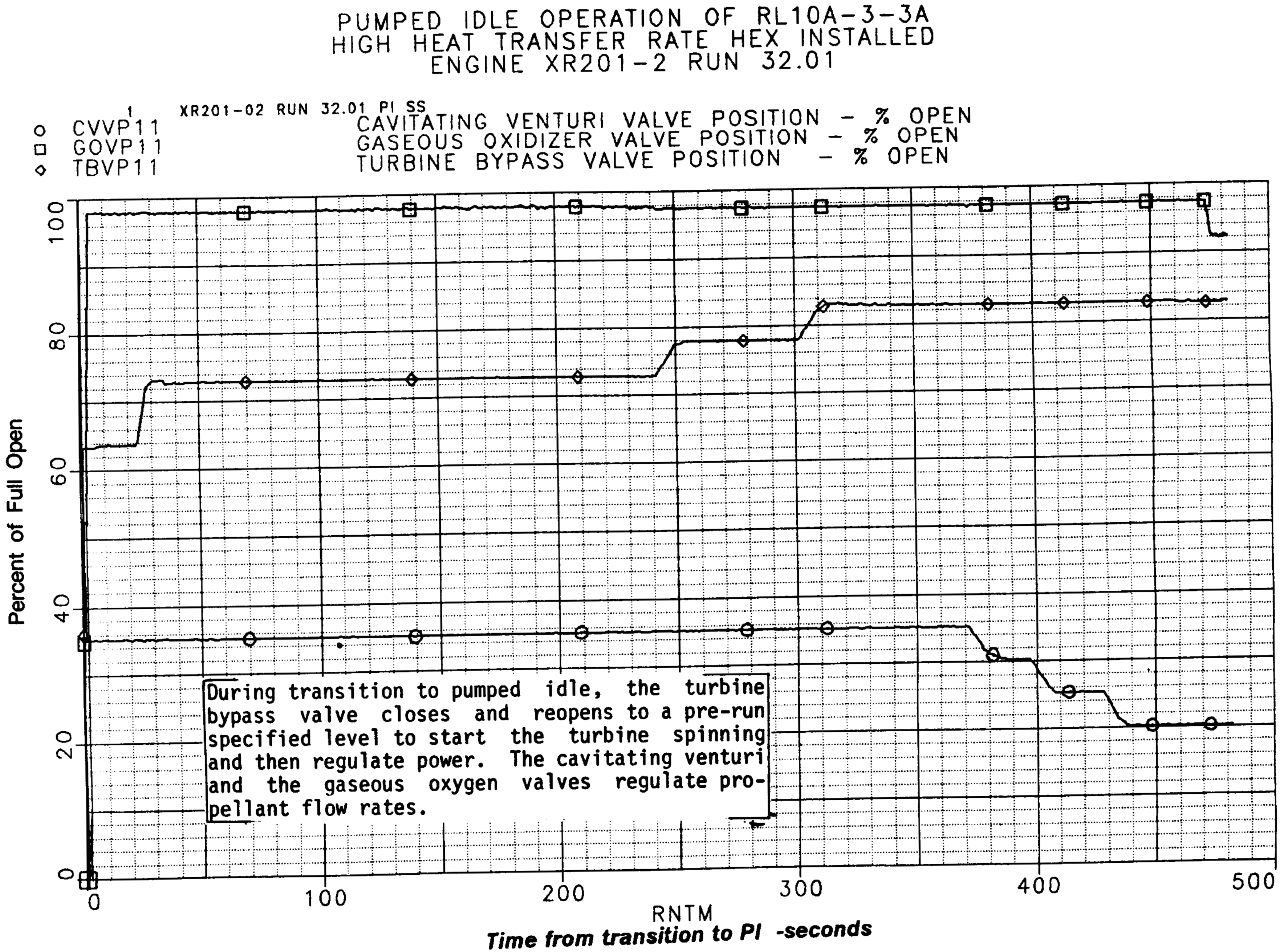


Figure C-4.

R182160/8

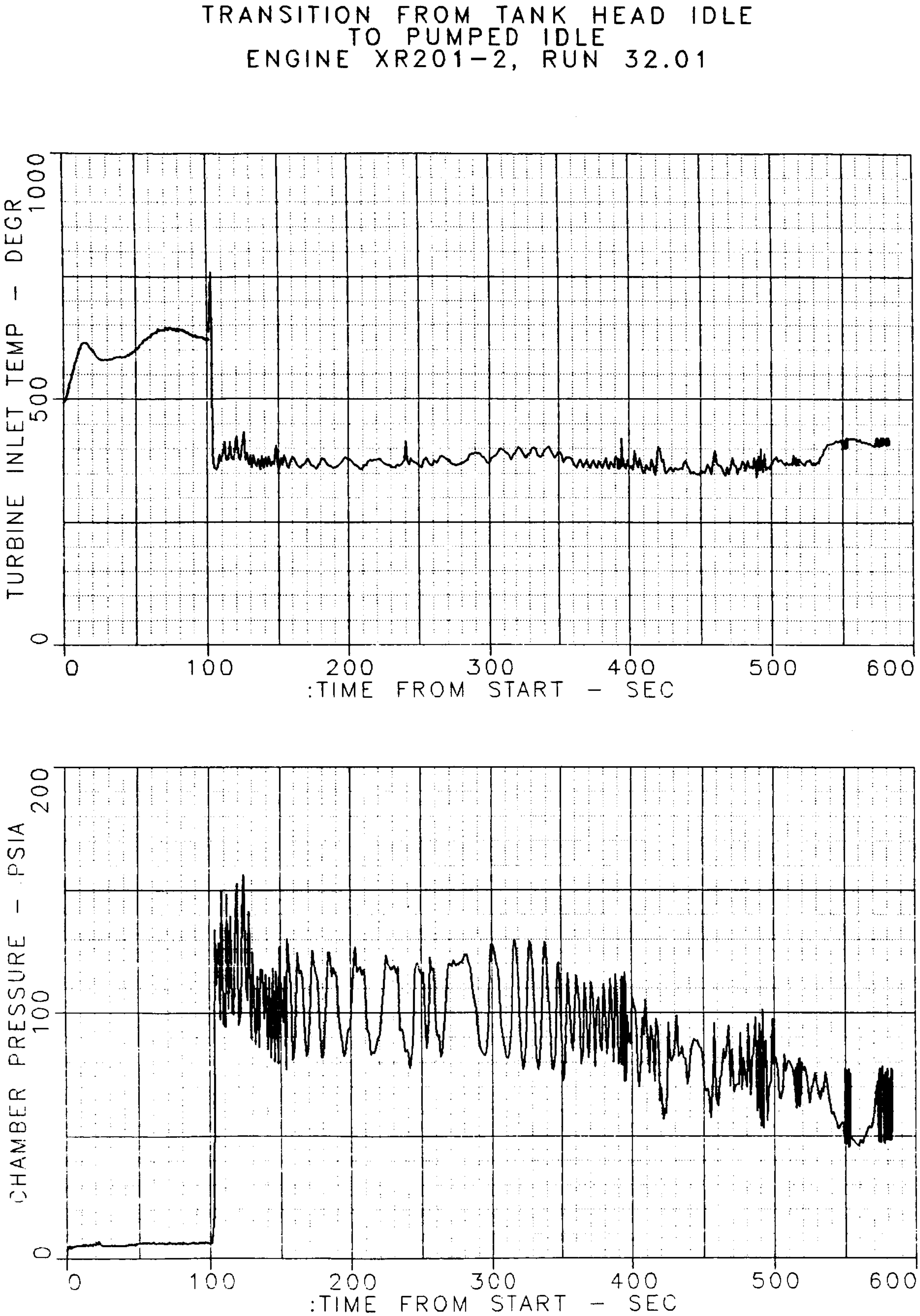

TRANSITION FROM TANK HEAD IDLE
TO PUMPED IDLE
ENGINE XR201-2, RUN 32.01
TURBINE INLET TEMP - DEGR
0
500
1000
0
100
200
300
400
500
600
:TIME FROM START - SEC
CHAMBER PRESSURE - PSIA
0
100
200
0
100
200
300
400
500
600
:TIME FROM START - SEC

Figure C-5.

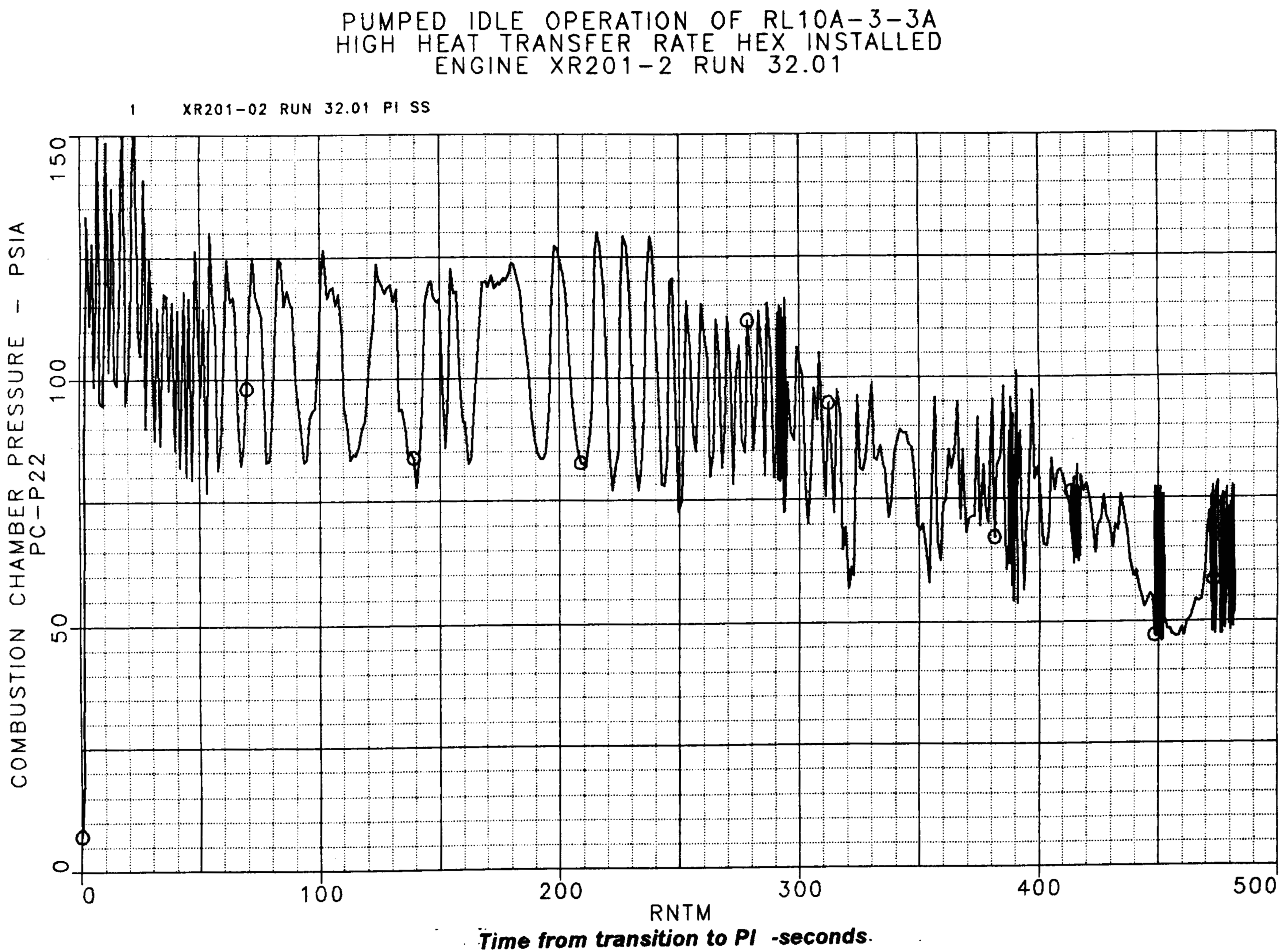


Figure C-6.

R182160/8

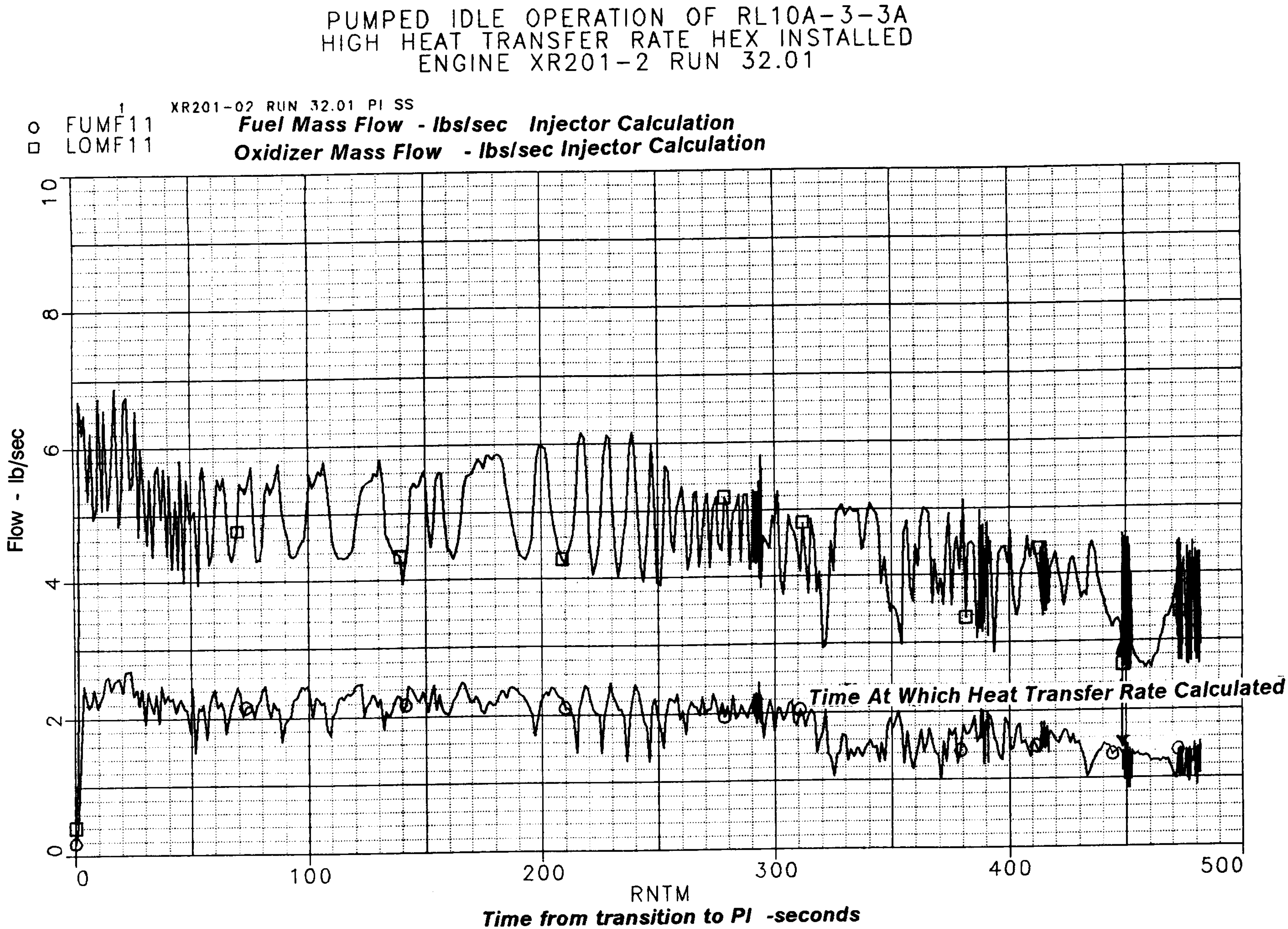


Figure C-7.

R182160/8

TABLE C-1. — XR201-2 TEST SUMMARY

Run No.	Date	Hot Time (sec)	Accumulated Hot Time (sec)	THI Time (sec)	PI Time (sec)	Inlet Pressure H_2	Inlet Pressure O_2	Run Summary	Valve Areas — Percent of Full Open: GOV Initial	GOV Final	THI CCV Initial	THI CCV Final	TBV Initial	TBV Final	PI GOV Initial	PI GOV Final	PI TBV Initial	PI TBV Final	CVV Initial	CVV Final
16.01	12-18-87	0.2	0.2	0.2	0.0	25.0	32.7	Low P_c (chamber pressure) abort. Increase abort time to allow engine to fill with fuel and evacuate fuel cooldown line.	21	99	100	100	93	100	N/A		N/A		N/A	
17.01	01-06-88	1.4	1.6	1.4	0.0	25.0	32.8	TSSV abort. The igniter induced noise on the turbine shutoff solenoid voltage.	22	22	100	100	91	91	N/A		N/A		N/A	
18.01	01-06-88	2.7	4.3	2.7	0.0	25.5	32.7	Low P_c abort. Increase abort time.	32	32	100	100	90	90	N/A		N/A		N/A	
19.01	01-06-88	146.1	150.4	146.1	0.0	25.2	32.8	Test engineer abort. Video of exhaust showed abnormal oscillation.	32	23	100	100	90	90	N/A		N/A		N/A	
20.01	01-08-88	11.1	161.5	11.1	0.0	39.1	32.8	High rpm abort. Disarm rpm abort during THI and rearm to PI. False abort.	22	22	100	100	92	92	N/A		N/A		N/A	
21.01	01-08-88	354.6	516.1	354.6	0.0	39.0	33.2	False high rpm abort. Noise was induced on rpm pickup.	32	17	100	100	92	91	N/A		N/A		N/A	
22.01	01-08-88	232.7	748.8	231.8	0.9	40.0	33.1	P_c/FPDP abort. The chamber pressure was too low for fuel pump discharge pressure. The abort is changed to allow lower P_c for a given FPDP.	22	17	100	100	93	92	17	22	100	20	0	57
23.01	01-11-88	142.4	891.2	140.9	1.5	40.6	33.0	P_c/FPDP abort. Disarm the abort.	21	16	100	100	91	91	N/A		N/A		N/A	
24.01	01-12-88	132.5	1023.7	129.0	3.5	39.8	32.9	FPDP abort. The LOX pump wasn't pumping, and P_c was falling off. No changes to abort.	21	16	100	100	92	91	16	36	36	36	0	52
25.01	01-12-88	117.8	1141.5	117.7	0.1	38.9	32.9	P_c abort. Turbine shutoff valve not responding to TSSV. The oxygen flow control valve has been leaking and is removed. The OCV plumbing is capped.	22	17	100	100	92	91	17	17	100	100	0	32
26.01	01-13-88	83.2	1224.7	83.2	0.0	40.0	33.3	P_c abort at transition to PI. Oxygen flow was low.	22	17	100	100	92	92	N/A		N/A		N/A	
27.01	01-13-88	258.4	1483.1	254.3	4.1	40.6	31.8	High HS-P abort 4.1 sec into PI. Half-shell pressure allowed to rise for 10 sec into PI in later runs.	22	36	100	100	92	91	36	54	100	34	0	64

TABLE C-1. — XR201-2 TEST SUMMARY (CONTINUED)

Run No.	Date	Hot Time (sec)	Accumulated Hot Time (sec)	THI Time (sec)	PI Time (sec)	Inlet Pressure H_2	Inlet Pressure O_2	Run Summary	Valve Areas — Percent of Full Open: THI GOV Initial	THI GOV Final	THI CCV Initial	THI CCV Final	THI TBV Initial	THI TBV Final	PI GOV Initial	PI GOV Final	PI TBV Initial	PI TBV Final	PI CVV Initial	PI CVV Final
28.01	01-13-88	138.6	1621.7	138.5	0.1	39.4	32.0	P_c abort similar to run 25.01. Turbine shutoff valve solenoid is replaced.	22	36	100	100	91	91	36	35	99	86	0	64
29.01	01-14-88	132.8	1754.5	126.5	6.3	40.4	31.5	P_c abort. Changed abort to allow lower P_c early in PI.	22	36	100	100	91	91	36	55	100	38	0	66
30.0	01-14-88	134.4	1888.9	130.9	3.5	39.2	32.6	Same test run as runs 28.01 and 29.01 with similar results. P_c abort. Changed abort to allow yet lower P_c early in PI.	22	37	100	100	91	91	37	63	100	21	0	64
31.01	01-15-88	429.2	2318.1	125.3	303.9	40.1	34.3	Successful transition to PI; however, flow rates and pressures could not be stabilized or brought to predicted levels. PI portion of run tape was bad.	20	33	100	100	90	88	—		—		—	
32.01	01-15-88	583.5	2901.6	101.4	482.1	39.9	34.6	Successful THI start and transition to PI; however, flow rates and pressures could not be stabilized to predicted levels During the transition to PI the TBVP (turbine bypass valve position) is fully closed for 100 msec and then opened 23%. The CVVP (cavitating venturi valve position) closes from 100% to 35% open. 0.9 sec after the transition to PI the GOVP opens 55%. After 3 sec the GOVP opens 98%. These are large oscillations in the oxygen system resulting in as large an amplitude as 50 psia in P_c. The TBVP is opened to 78%, P_c-P22 decreases 5 psia, and the fluctuations increase. LOMF (Liquid Oxygen Mass Flowrate) decreased by 0.4 lb/sec. The TBVP is opened to 83%, P_c-P22 decreases 15 psia, and the fluctuations decrease significantly. LOMF decreased by 0.5 lb/sec, and its oscillations also decreased. The	20	34	100	100	90	88	33	92	100	20	0	82

TABLE C-1. — XR201-2 TEST SUMMARY (CONTINUED)

									Valve Areas — Percent of Full Open											
						Inlet Pressure			GOV		THI CCV		TBV		GOV		PI TBV		CVV	
Run No.	Date	Hot Time (sec)	Accumulated Hot Time (sec)	THI Time (sec)	PI Time (sec)	H_2	O_2	Run Summary	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
								CVVP was then decreased by 5%, P_c-P22 oscillations increased in amplitude and frequency, and the overall P_c-P22 increased by 5 psia.												
33.01	01-19-88	3.1	2904.7	3.1	0.0	39.8	34.7	The low heat transfer heat exchanger was installed. P_c abort. False abort due to built-in inaccuracy in the abort system.	22	22	100	100	94	94	—		—		—	
34.01	01-19-88	369.4	3274.1	369.4	0.0	40.0	34.2		23	42	100	100	93	93	—		—		—	

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TABLE C-2. — HEAT EXCHANGER HEAT TRANSFER PERFORMANCE

Time Of Data	*Run*	*H_2 Side Δ Pressure*	*H_2 Side Δ Temperature*	*Fuel Flow (lb/sec)*	*Transfer Rate (BTU/sec)*	*Q_{Fuel} Heat 0_2 Side Δ Pressure*	*0_2 Side Δ Temperature*	*Oxygen Flow (lb/sec)*	*Q_{Oxygen} Heat Transfer Rate (BTU/sec)*
				Tank Head Idle					
124.62	26.01	6.45	82.65	0.147	42.32	1.23	38.41	0.266	25.67
235.20	27.01	7.09	160.43	0.143	80.19	2.14	349.23	0.392	65.23
170.17	28.01	6.87	173.72	0.136	82.71	2.15	411.82	0.368	65.98
171.69	29.01	9.43	139.59	0.163	79.42	3.78	343.97	0.397	30.30
162.95	30.01	8.62	178.71	0.143	89.46	1.10	404.23	0.379	34.03
144.97	31.01	7.44	182.22	0.154	98.07	1.57	342.18	0.431	70.64
53.53	32.01*	5.71	297.71	0.150	156.63	0.60	66.72	0.280	44.35
218.45	34.01	4.97	73.04	0.209	54.95	0.41	348.89	0.303	50.05
409.44	34.01	4.39	127.49	0.167	74.26	0.72	484.50	0.383	74.95
				Pumped Idle					
593.34	32.01	6.01	178.94	1.0091	693.06	13.6	29.13	7.293	648.78

* Engine is not thermally stabilized.

NOTE
1. Run 26.01 through 32.01 — High Heat Transfer Rate Heat Exchanger
2. Run 34.01 — Low Heat Transfer Rate Heat Exchanger
3. THI flows are calculated using the injector equation
4. PI flows are calculated using the flow meter equation.

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TABLE C-3. — HIGH-HEAT TRANSFER HEAT EXCHANGER THI CHARACTERISTIC COMPARISON

	Flowrate (lb/sec)	Inlet Temperature (°R)	Outlet Temperature (°R)	Inlet Pressure (psia)	ΔPressure	Heat Transfer (Btu/hr)
Design						
• LO	0.31 ± 0.05	165.8	311.0	20.0	0.88	151,338
• GH_2	0.094	594.0	167.9	9.0	0.4	
Run 26.01						
• LO_2	0.26 ± 0.005	177.6	216.0	33.78	1.23	92,412
• GH_2	0.15	682.3	600.0	18.4	6.45	152,352
Run 27.01						
• LO_2	0.39 ± 0.01	177.1	526.3	32.7	2.1	234,828
• GH_2	0.14	817.2	656.8	19.3	7.1	288,684
Run 28.01						
• LO_2	0.37 ± 0.002	176.6	588.5	32.4	2.2	237,528
• GH_2	0.14	847.5	673.7	18.6	6.9	297,756
Run 29.01						
• LO_2	0.40 ± 0.008	177.5	521.5	31.8	3.8	109,080
• GH_2	0.16	788.7	649.1	22.5	9.4	285,912
Run 30.01						
• LO_2	0.38 ± 0.008	177.6	581.8	30.124	1.1	122,508
• GH_2	0.15	849.4	670.7	20.3	8.7	322,056
Run 31.01						
• LO_2	0.43 ± 0.006	176.6	518.8	35.8	1.57	254,304
• GH_2	0.15	823.9	641.8	20.3	7.4	353,052
Run 32.01*						
• LO_2	0.28 ± 0.01	178.8	245.5	34.3	0.6	15,660
• GH_2	0.15	795.9	498.2	16.3	5.7	267,336
Design						
• LO_2	0.31 ± 0.05	165.8	589.0	20.0	0.5	
• GH_2	0.094	594.0	416.0	9.0	2.03	205,020
Run 34.01						
• LO_2	0.38 ± 0.024	175.5	660.0	33.3	0.7	269,820
• GH_2	0.17	697.6	570.1	17.2	4.4	267,336

* Engine is not thermally stabilized

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TABLE C-4. — HIGH-HEAT TRANSFER HEAT EXCHANGER PI CHARACTERISTIC COMPARISON

	Flowrate (lb/sec)	*Inlet Temperature (°R)*	*Outlet Temperature (°R)*	*Inlet Pressure (psia)*	*ΔPressure*	*Heat Transfer (Btu/hr)*
Design						
• *LO*	2.84 ± 0.20	168.0	256.0	110.0	4.3	1,115,730
• *GH_2*	0.19	659.0	209.0	46.7	2.1	
Run 32.01						
• *LO_2*	3.29 ± 0.98	173.2	216.5	138.10	13.6	2,335,608
• *GH_2*	1.3	409.6	230.7	83.69	6.01	2,495,016

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16. Abstract

Cryogenic rocket engines requiring a cooling process to thermally condition the engine to operating temperature can be made more efficient if cooling propellants can be burned. Tank head idle and pumped idle modes can be used to burn propellants used for cooling, thereby providing useful thrust. Such idle modes required the use of a heat exchanger to vaporize oxygen prior to injection into the combustion chamber.

During December 1987 and January 1988, Pratt & Whitney conducted a series of engine hot firings demonstrating the operation of two new, previously untested oxidizer heat exchanger designs. The program was a second iteration of previous low thrust testing conducted in 1984, during which a first-generation heat exchanger design was used.

Although operation was demonstrated at tank head idle and pumped idle, the engine experienced instability when propellants could not be supplied to the heat exchanger at design conditions.

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